DEVELOPMENT OF A MODEL FOR DETERMINING WORKZONE ILLUMINATION REQUIREMENTS DURING NIGHTTIME HIGHWAY CONSTRUCTION

By

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WORKZONE ILLUMINATION REQUIREMENTS DURING
NIGHTTIME HIGHWAY CONSTRUCTION

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With the increasingly popularity of nightwork on many highway construction projects, a number of complex problems have been introduced in highway rehabilitation. Of many issues involved, workzone lighting is found to be the single most important factor affecting quality, safety, cost and productivity on these night projects. At present, lighting requirements in the workzones are minimally defined in the specifications of few state highway agencies and often times are not formally designed as there is no standard or guidelines to go by. Although a number of research studies have been performed in roadway lighting and industrial lighting area, no formal study determining illumination requirements in the workzones has been conducted. In this research effort an attempt has been made to identify the typical highway construction tasks performed at night and the factors affecting illumination requirement to adequately conduct these operations, and to develop a model

determining average maintained light intensity levels for the tasks.

In an effort to provide an overview of nighttime highway construction and provisions for lighting, an extensive literature review was conducted. As a result of nationwide questionnaire survey, various highway operations commonly performed at night were identified. Significant factors influencing illumination requirements for workzone lighting were also identified. These factors included - a) speed, b) accuracy or importance, c) reflectance, d) seeing distance, and e) size of object. These factors were assigned certain subjective levels for comparing with visually similar outdoor industrial tasks. Various illuminance level categories were determined based on IES and OSHA recommendations, state provisions, opinions of experts and experiences during field reviews. The categories were intended to be interpreted as recommended safety requirements and not regulatory minimum requirements. A model approach was adopted to determine illumination levels for any given construction task. Correlation analysis was performed to examine the association of various factors with illumination requirement. Trial models were suggested and analyzed using SAS procedures. The most appropriate model was selected and validated using three real life case studies. For all the case studies which represented most commonly performed highway construction tasks at night, the results conformed to the field recorded values. From the opinions of the crew at the job-site and experiences while recording the observations, it was concluded that the results from the model were in agreement with the findings.

CHAPTER 1
INTRODUCTION AND PROBLEM STATEMENT

Overview of Nighttime Highway Construction

Recently many states have changed the direction of their operations from new highways and roads to maintaining the existing ones. The emphasis has shifted from building new facilities to maintaining and improving those in existence. This shift creates many problems. One such problem arises from daytime lane closures which results in heavy congestion on roads already loaded to capacity. This problem is not limited to roads in urban areas, but also includes some rural highways that are often as crowded during certain times of the year as urban areas. According to a state highway agency official, it has become hard to separate the morning rush hours from evening rush hours and congestion lasts for 12-13 hours a day. This creates the situation where the natural, ordinary solution of lane closure becomes unrealistic or impossible during peak times. The daytime lane closures are also hazardous, costly and inconvenient for the traveling public. As a result, more construction and rehabilitation work is being performed during hours when traffic flow is minimal. For this reason many highway agencies have started working at night. In addition to several obvious advantages of nighttime work such as cooler temperatures for equipment and material, less traffic problems, and delays, there are certain complex issues involved, which include safety, costs, productivity, lighting conditions, manpavailability, and administrative decisions.

A recent research study conducted at the University of Florida performed an extensive literature survey and discussed various issues related with nighttime highway construction (1). The literature review from the study on highway construction also confirms this trend of increased nightwork and addressed the problems associated with it. However, the number of references dealing directly with the night shift operations, as a whole, are limited. Only a few studies provide a comprehensive approach and valuable information towards night shift construction. In the study based on the literature survey, analysis of several case studies, and meetings with experts in Florida and other states, a number of factors were identified that affect the decision of shift times for highway construction. These factors play important roles in determining whether or not to work at night. Based on their characteristics, they are divided into five categories and presented in Figure 1.1. A listing of the categories with respective factors follows:

1) Construction related factors

    a) cost, b) productivity, c) quality, d) noise

2) Traffic related factors

    a) congestion, b) safety, c) traffic control

3) Human factors

    a) sleep, b) circadian rhythms, c) social/domestic issues

4) Miscellaneous factors

    a) public relation, b) information, c) supervision,

    d) communication, e) material supply, f) equipment repair

5) Work zone lighting.

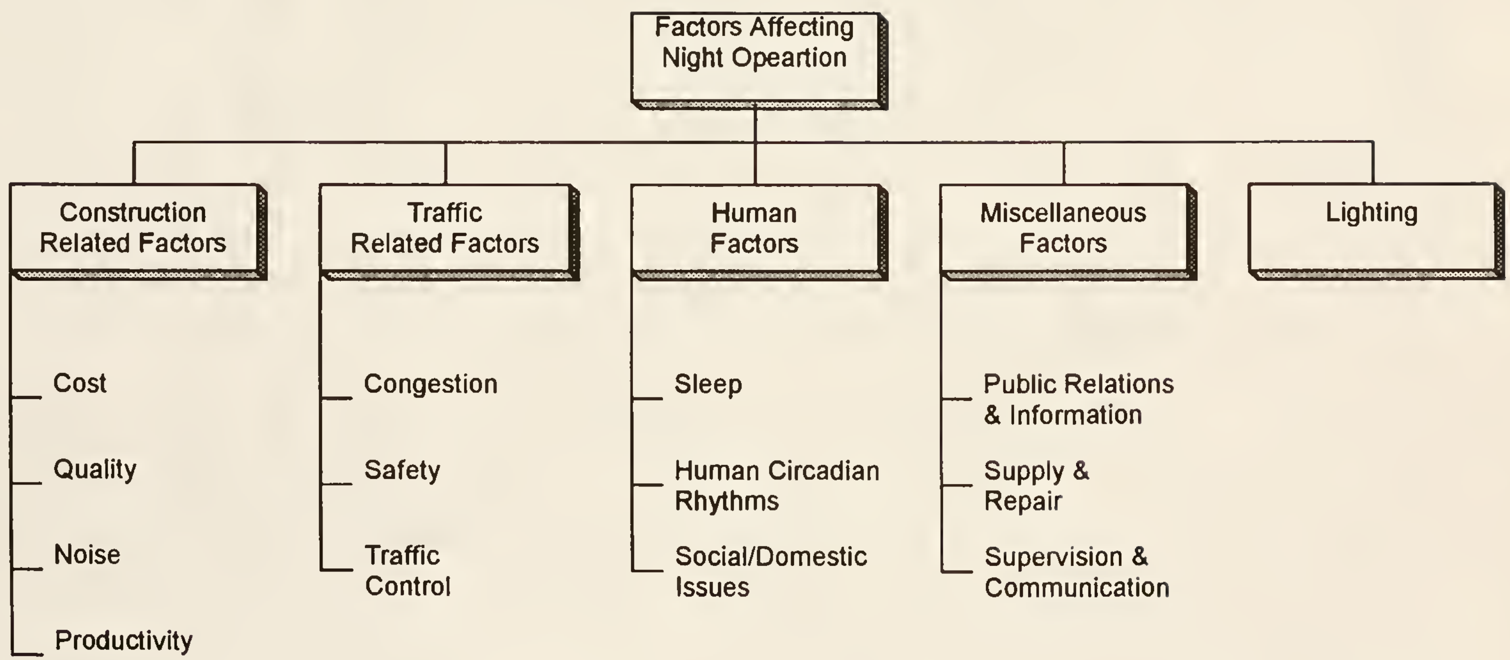


Figure 1.1 Summary of Factors Affecting Night Operations Source: Ref. 1

Some of these factors have qualitative and some quantitative attributes. For instance, cost and productivity are quantitative factors; quality, noise, safety, and congestion are both qualitative and quantitative; and human factors and other factors are qualitative. As a result of analysis of construction related factors, it is found that cost, quality, and productivity had some project-by-project variations due to various reasons. Cost, productivity and quality are the basic project attributes and are affected by the way work is performed. There have been various opinions with regard to variations in these factors as a result of a change in workshift. According to some opinions, construction costs and total project costs are normally expected to be higher in the case of night construction as opposed to day construction. The reasons are attributed to overtime, shift differential, lighting, higher bids etc. However, user and public costs may follow a reverse trend. Similarly nighttime work may have negative effects on quality and productivity. The number of noise complaints are higher for nighttime work if projects are in urban areas and take a longer time to finish. Although human factors are usually given some consideration, they do not constitute a major decision-making criterion. Traffic related factors are considered to be the most important when deciding about night work. Congestion is often found to be the one single factor resulting in the decision to use a night shift on many projects. Safety is one of the major concerns during night work because accidents tend to be more severe, even though the rate is relatively low. To enhance safety appropriate traffic control is emphasized and slower speeds, lane closures, detours, use of flashing arrow boards, use of appropriate warning devices, layouts, sufficient lighting and use of police patrol cars are found to be some of the more effective measures for better traffic control. In addition, public relations and information are found to be important elements in nighttime construction. Not only do announcements reduce the congestion and accident rate,

but the public has a positive attitude towards the delays and noise. Supervision and communication are difficult for nighttime work because most offices are open during the daytime. Similarly, supply and repair also create some problems since parts and materials are not easily available at night. Although most of these factors have some effect on night work, work zone lighting has a considerable influence. It not only affects quality and productivity, but also influences traffic control, safety and human factors.

Need for Adequate Lighting

A study conducted at the University of Florida has shown lighting as one of the most important factors for nighttime construction (1). It has been found that safety in the workzone, traffic control, quality of work and worker's morale are directly related to workzone lighting. Limited or restricted visibility is an obvious drawback of nighttime construction. However, with adequate levels of light, construction operations can be performed as well at night as they can be during the day. Likewise, the key factors that influence accident rates are the physical conditions of drivers and the light conditions of the environment. The physical conditions of the driver may include conditions such as drowsiness and sensitivity to light glare. Worker injury rate also increases due to the inherent vision impairment associated with nighttime lighting conditions (2). Sufficient lighting of the work area is also important from the point of view of quality. Standard highway lighting, or light from nearby businesses or residences, is generally inadequate to properly light the areas where work is performed. Inadequate lighting results in problems with proper inspection. Work quality is affected because many defect causes can not be properly controlled such as shadows, tack spread, asphalt droppings (3).

Problem Statement

In the specifications of many state highway agencies present lighting requirements are minimally defined (e.g. minimum intensity level of 5 ft-candles, sufficient light to permit good workmanship and proper inspection). Most of these specifications are not only inadequate but also not standardized. All the decisions pertaining to workzone lighting are left at the discretion of the site engineer and the contractor. Moreover due to the lack of criteria related to average illumination levels and uniformity of illumination, lighting systems can not be designed satisfactorily.

Various question arise related to this issue which include the following:

1) What should be the definition, size and dimension of workzone area during nighttime work ?

2) How far should the view of the construction equipment operator be extended to satisfactorily perform the task?

3) What is the minimum illumination requirement for adequate visibility and comfort?

4) What are the factors that determine quantity and quality of light for any particular task?

5) How can the average illuminance for typical construction and maintenance tasks be determined?

6) How can the requirement of illuminance levels for any given task be predicted and determined?

7) What is the minimum illuminance level required for work inspection and quality control?

8) What should be the extent of lighted area around the equipment for the workers to work comfortably ?

9) Is there any need of portable or fixed lights in the workzone?

10) How can the discomfort glare to the motorists and the workers be reduced and avoided?

These questions warrant the need and importance of a study which can provide satisfactory approach to solving such problems. Although lighting is the single most important factor in nighttime construction, it is least studied. Very little research has been done concerning the proper lighting of construction sites. Although a number of studies concerning various lighting aspects such as industry lighting, roadway lighting, and building lighting are conducted. They are considerably different from construction site lighting and can not be directly applied.

Research Objectives

In the light of previous discussion it becomes imperative to conduct a research effort which not only can suggest the design of illuminance levels based on current site conditions, but also facilitate developing set of standard guidelines and specifications. The main objective of this research effort is to develop a model approach to determine the illuminance levels for nighttime highway construction tasks and to develop and recommend guidelines for these tasks. To fulfill the main objective of the study, it has been divided into several sub-objectives which are as follows:

1) To review the fundamental lighting concepts from literature, state-of-the-art of lighting, and current practices in nighttime construction. The intent is to determine the typical highway construction and maintenance activity list commonly performed at night. This also includes determining the factors that affect illuminance requirements for a particular task and assigning levels to these factors for numerical comparison purposes.

2) To develop a regression model which can best fit the data of existing standards and can be used as a prediction model for highway operations.

3) To develop the guidelines by comparing highway and non-highway tasks which consists of illumination categories, recommended levels for typical tasks and equipment.

4) To validate the model by analyzing several real life case-studies and comparing the results with the ones observed in the field. Suggestions will also be provided for model modification, improvements and future research.

The detailed research work plan has been provided in the subsequent section. Figure 1.2 shows the schematic flow chart, which explains exactly how the above stated objectives are accomplished.

Research Methodology

To accomplish the objectives of this study several tasks were completed. A comprehensive review of published information in the study area was conducted. Literature pertaining to visual task evaluation, and role of illuminance, contrast and reflectance in visibility of objects were collected from all relevant U.S. and international electronic data bases. This document retrieval process also included obtaining existing illumination standards for similar outdoor activities.

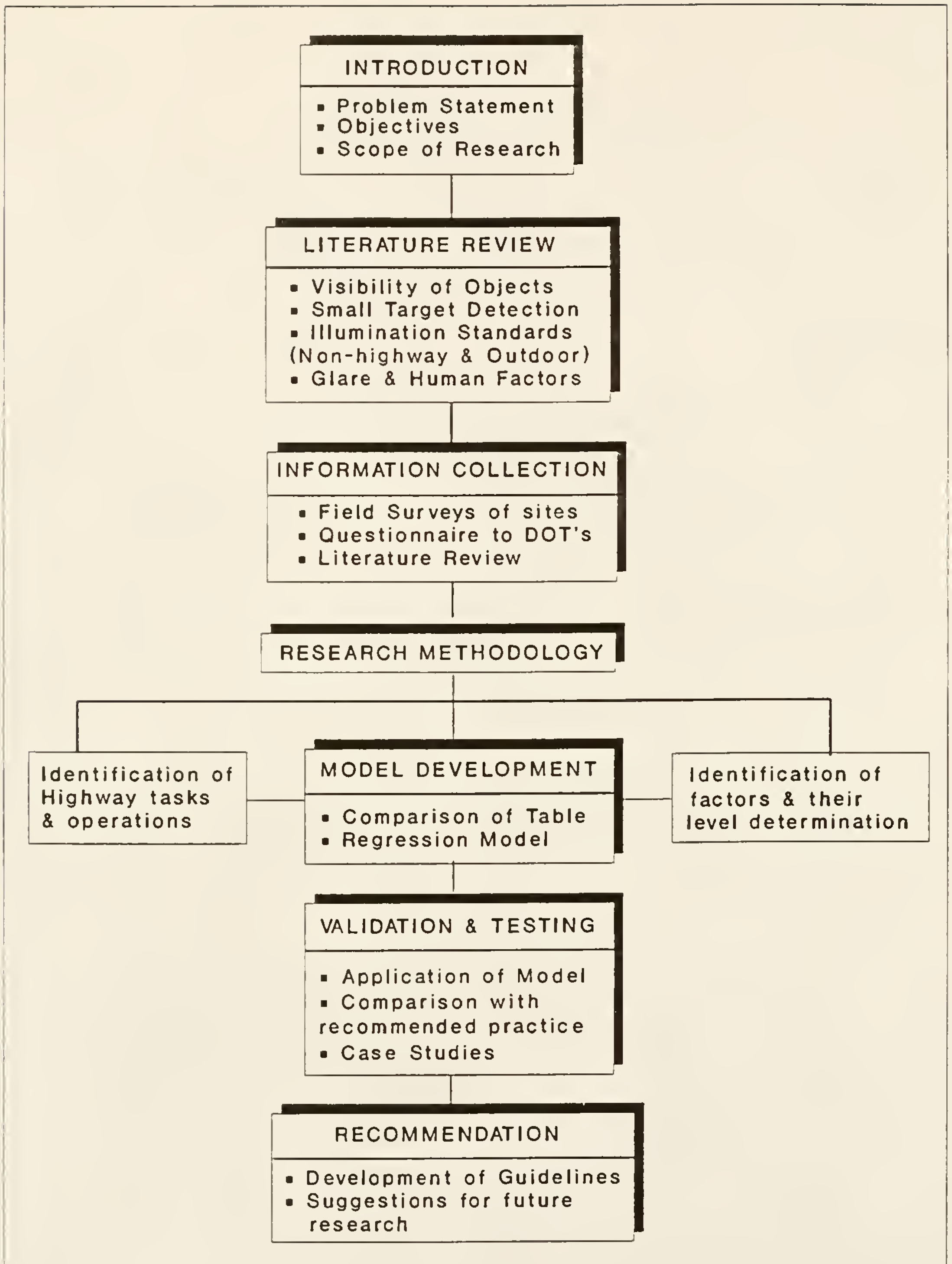


Figure 1.2 Schematic Flow Chart of Research Work Plan

Principal equipment manufacturers and lighting manufacturers were contacted to obtain a summary of information concerning available lighting equipment. A questionnaire was prepared to be sent to all state highway agencies. The purpose of this survey was to obtain information concerning the range of construction and maintenance activities performed at night, and illumination criteria used by different state highway agencies.

A number of nighttime highway construction sites were visited to collect data about current practice. These visits served to document the information about type and configuration of lighting equipment in use, light intensity levels currently being obtained, and workers' perspectives. This field survey involved video taping of various work activities being performed at night and measurement and recording of light intensity levels. Field reviews were targeted at the types of construction and maintenance activities most commonly performed at night.

Identification of various factors which have significant influence on determining adequate illuminance levels was done. This identification was based on the review of literature and experience of experts. Various subjective levels were assigned to these factors to develop nighttime lighting requirements for highway workzones by transferring relevant standards from similar non-highway activities. This was accomplished primarily by determining the "seeing tasks" and worker needs for the highway activities and then identifying non-highway activities with similar "seeing tasks" and worker needs.

Using SAS software, correlation analysis was performed to evaluate the level of significance of various factors. The factors having high correlation were selected for model development. A series of model were proposed and tested using different criteria for their adequacy to represent the data well. The model best-fitting the data was selected and chosen

as the regression equation for future predictions. This model was then tested by examining three undergoing nighttime projects in the state of Florida. The model was applied to determine the levels for typical tasks performed in each operation and compared with the actual recording of levels and workers' opinions. These case-studies validated the model developed for prediction of illuminance level for any nighttime construction activity.

A set of guidelines were also recommended for all typical construction and maintenance tasks identified earlier. For the guidelines, several illumination categories were developed and illumination ranges were recommended. These categories followed the approach suggested for lighting in other industries. Recommendations for improving and modifying the model have also been included as suggestions for future research.

CHAPTER 2
OVERVIEW OF STATE-OF-THE-ART

Introduction

In an attempt to provide an overview of state-of-the-art, an extensive literature survey has been conducted to obtain the most up-to-date and relevant data pertaining to illumination of construction workzones. A computerized search of electronic databases including Southern Technology Application Center (STAC) and Transportation Research Information Services (TRIS) resulted in more than 100 published papers and articles. Additional reference materials were obtained through the Illumination Engineering Society of North America (IESNA) and the International Commission on Illumination (CIE). Although no articles were found that directly addressed the topic of construction workzone illumination, many were found in related areas such as roadway lighting, industrial lighting, surface mine illumination, sports lighting, and the fundamentals of visibility. The literature fell into four basic areas: the visual task, human factors, current practices and standards. In addition, literature review information pertaining to standards and guidelines was also collected through a questionnaire survey. Similarly, field investigation and survey contributed to the additional data on current practices. It should be noted that although the variables are very often discussed individually, a large number of inter-relationships exist.

Review of Literature

Based on the literature survey, it was determined that visual perception depends on a number of factors. The important factors include

1. Luminance in visual field
2. Contrast
3. Reflectance of the object and background
4. Physical properties of objects
5. Duration of exposure
6. Physiology of the observer's visual, neural and mental systems
7. Age
8. Psychological and cognitive factors

Of the above factors, the ones related to human issues such as adaptation, physiological and psychological considerations, and effect of physical properties of objects in performance and safety are discussed in the section addressing effects of human factors. The remaining factors are included in the section addressing evaluation of visual task.

Evaluation of Visual Task

Visual displays can be specified in terms of quantities of various parameters, which include: 1) luminance, 2) contrast, and 3) reflectance.

Luminance

Target luminance is an important controlling factor in visual acuity. Acuity is poorest under low levels of illumination and gradually increases to a limiting value as illumination is

increased. Results of research by Smith and Rea also confirmed that a certain minimum level of illumination is required for optimal task performance (4, 5, 6). However, exceeding this minimum by a significant amount will not cause performance to deteriorate, as long as glare is minimized or avoided.

Finch also emphasized that luminance is one physical parameter that must be prescribed as the basic quantity in the visual field (7). Luminance may cause a reaction within the observer's visual system that results in a subjective response termed "brightness." In addition to quantity considerations, the quality consideration associated with luminance is related to uniformity of luminance. With regard to seeing detail in the work area, uniformity is very important. Uniformity, depending on the requirement, can be measured in three ways: 1) minimum luminance in the visual field compared with the adaptation luminance, 2) the total luminance variation in the visual field, and 3) ratio of maximum and minimum luminance.

Although luminance is the parameter that directly affects visual perception, in addition to luminance values, a set of illumination values should also be prescribed. The primary reason for this is that the collective experience of roadway and other lighting designers in the country relates mainly to horizontal illumination values which makes the practitioners comfortable with a specification that requires known quantities (7). The relationship between luminance and illumination and their respective advantages are discussed in detail later in the section addressing various design criteria.

Contrast

Contrast is usually defined as the ratio of the luminance difference of target and background to the luminance of the background. When an object and its background are illuminated by a single source and the luminances are dependent on their reflectances, contrast

does not change by varying intensity of the source. However, since reflectance depends on the positions of observer and source, changing the position of the source may change contrast (8).

As the contrast of the object is raised, the probability of seeing increases until it can be detected 100% of the time. The contrast at which the object can be detected 50% of the time is called the threshold contrast. A fundamental relationship exists between object detection and the luminances of the background. According to IES, as the background luminance increases the contrast threshold decreases with a decreasing rate (8).

Ginsburg found that contrast sensitivity, and not visual acuity, helps predict an individual's ability to see an oncoming target or stationary object at the first possible moment (9). Gallagher and Meguire in their study of contrast in night driving found a strong correlation with driver performance (10). Contrast was found to be the most important element in determining visibility within the range of variables studied.

Reflectance

Reflectance of a surface is defined as the ratio of its luminance to the incident illumination. For highways, two types of reflectances are considered: 1) retroreflectance and 2) forward reflectance. Retroreflectance is defined as the percentage of lamp illumination returned by the highway surface to an observer on the same side of the lamp. Forward reflectance is the percentage reflected by the surface to an observer on the opposite side of the lamp.

Figure 2 1 shows the retroreflectance data for various road surfaces (11). In general, retroreflectance increases with increasing distance from the source.

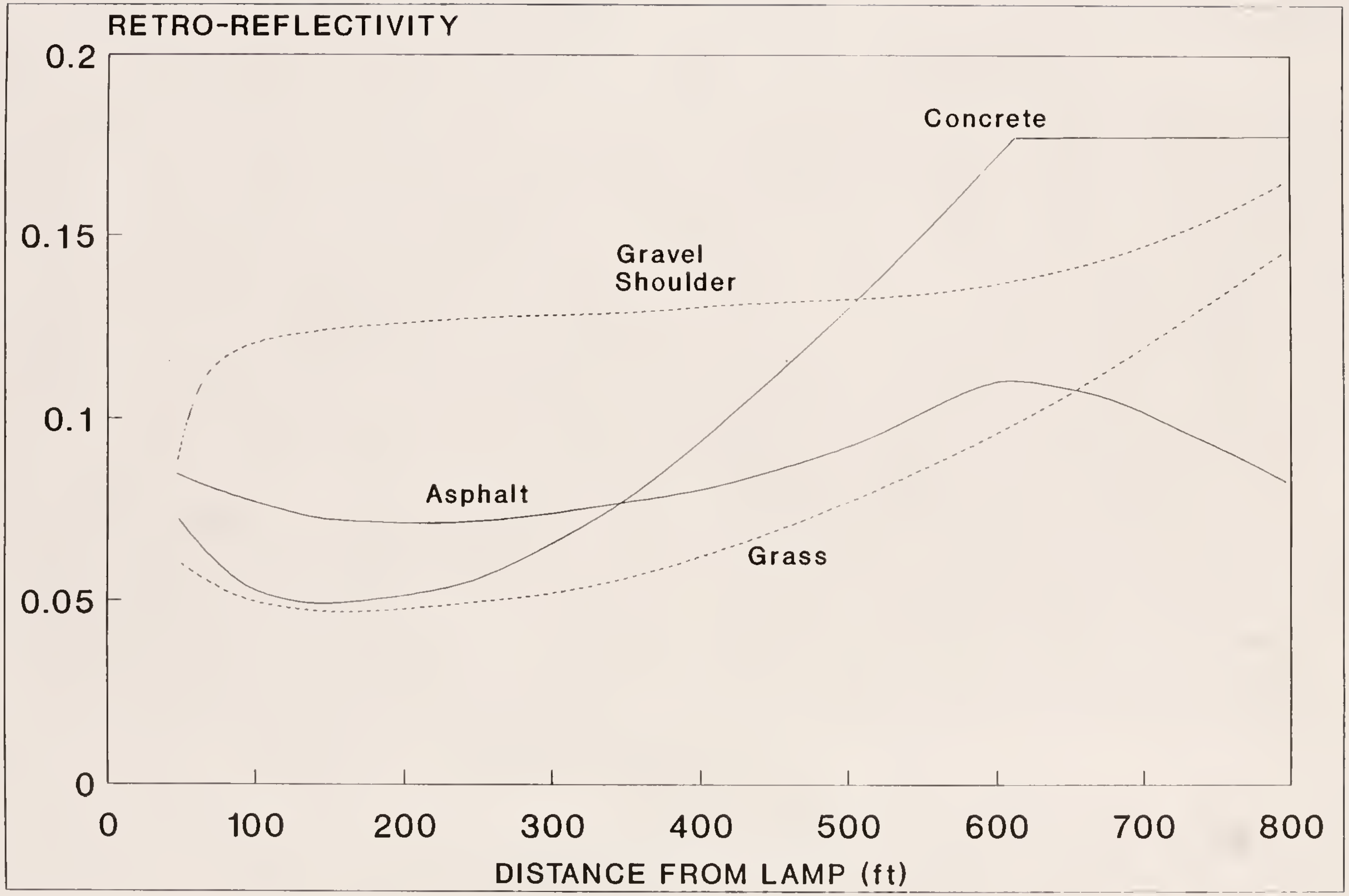


Figure 2.1 Retroreflectivity Coefficients as a Function of Distance for Various Road Surfaces <u>Source</u>: Ref. 11

However, it does not vary significantly with the lateral position of the measured point beyond a distance of 100 ft. Forward reflectance values are usually 10 to 100 times greater than retroreflectance values because of a large specular component. Maximum values lie along the source-observer axis and peak at a point that lies between the lamp and the midpoint of the axis.

Design criteria.

The objective of lighting design is to provide the proper quantity and quality of light based on several economic and practical considerations. However, quantity and quality of light required for a particular task is governed by the design criteria. As pointed out in IES, in the past there was an overwhelming emphasis on delivering sufficient quantity of light on the task or work surface (8). Quality of light has been considered mainly in controlling direct and reflected glare, and uniformity. However, with advancements in lighting research, a systematic change in the objectives of light design and requirements was observed. In 1982, the Roadway Lighting Committee of IESNA approved a revision to the Standard Practice for Roadway Lighting (12). This revision incorporated design criteria based on pavement luminance, luminance uniformity and veiling glare as the preferred and equally acceptable method for roadway lighting. The old method was based solely on horizontal illuminance.

The three major design criteria are: 1) illuminance criteria, 2) luminance criteria, and 3) visibility criteria.

Figure 2.2 depicts the differences among the three criteria. Each of these criteria requires determination of different physical variables and differs in terms of expected accuracy and measurement. If illuminance calculations are performed based on only lamp wattage, an accuracy as low as ±100% is obtained, whereas for illuminance computations utilizing light

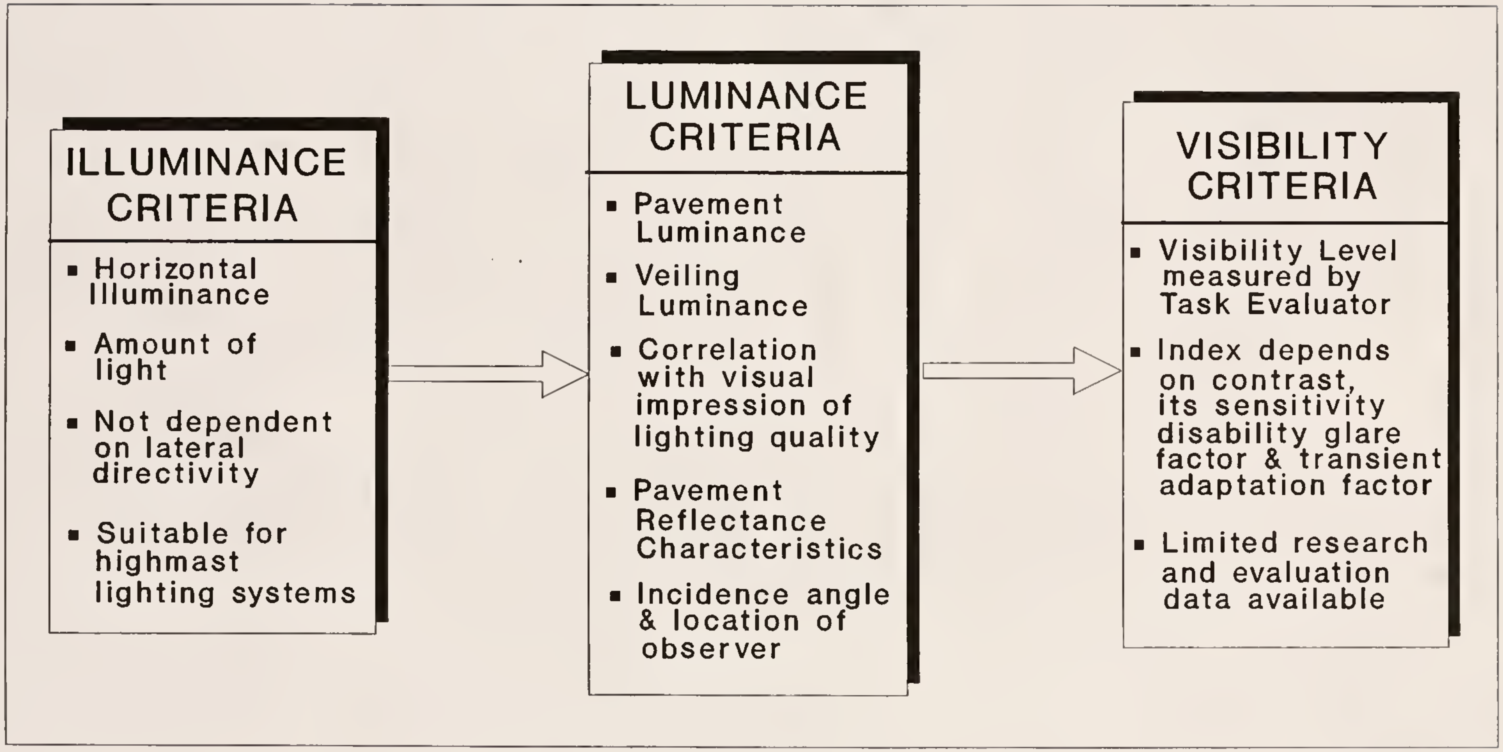


Figure 2.2 Comparison of Various Lighting Design Criteria <u>Source</u>: Ref. 8

source distribution information can result in an expected accuracy is ±5%. The accuracy is prescribed by the importance of the result weighed against the cost and complexity of the calculation (8).

Illuminance criteria for a surface requires a certain quantity of light reaching that surface directly from the source and by reflections from other surfaces. Illuminance (E) is defined as incident luminous flux (I) per unit area and is given by Lambert's cosine law as

$$E = I \cos \theta / d^2$$

where θ is the angle of incidence and d is the distance between the source and the point (8). Although other criteria determine better visibility compared to illuminance criteria, many regulations recommend illuminance levels for specifications. Illuminance, despite its limitations of determining accurate visibility, is more useful for design purposes as well as for quality control of illumination due to easy measurement and less complex computations (13).

Luminance criteria provides information regarding the appearance of objects and surfaces, their contrast and luminance ratios. Determination of luminance requires computation of illuminance on a surface and its reflectance characteristics. Luminance is directly proportional to the product of illuminance and surface reflectivity. Weis has given the relationship between luminance and illuminance for various surfaces of diffused reflectance as shown in Figure 2.3 (13). The figure also shows the typical ranges of reflectivity for various highway construction related objects.

Visibility criteria, which is a relatively newer concept, is an extension of luminance criteria. Blackwell developed a conceptual framework and instrumentation for measurement of the visibility level (14). The quantity is measured with a visual task evaluator (VTE),

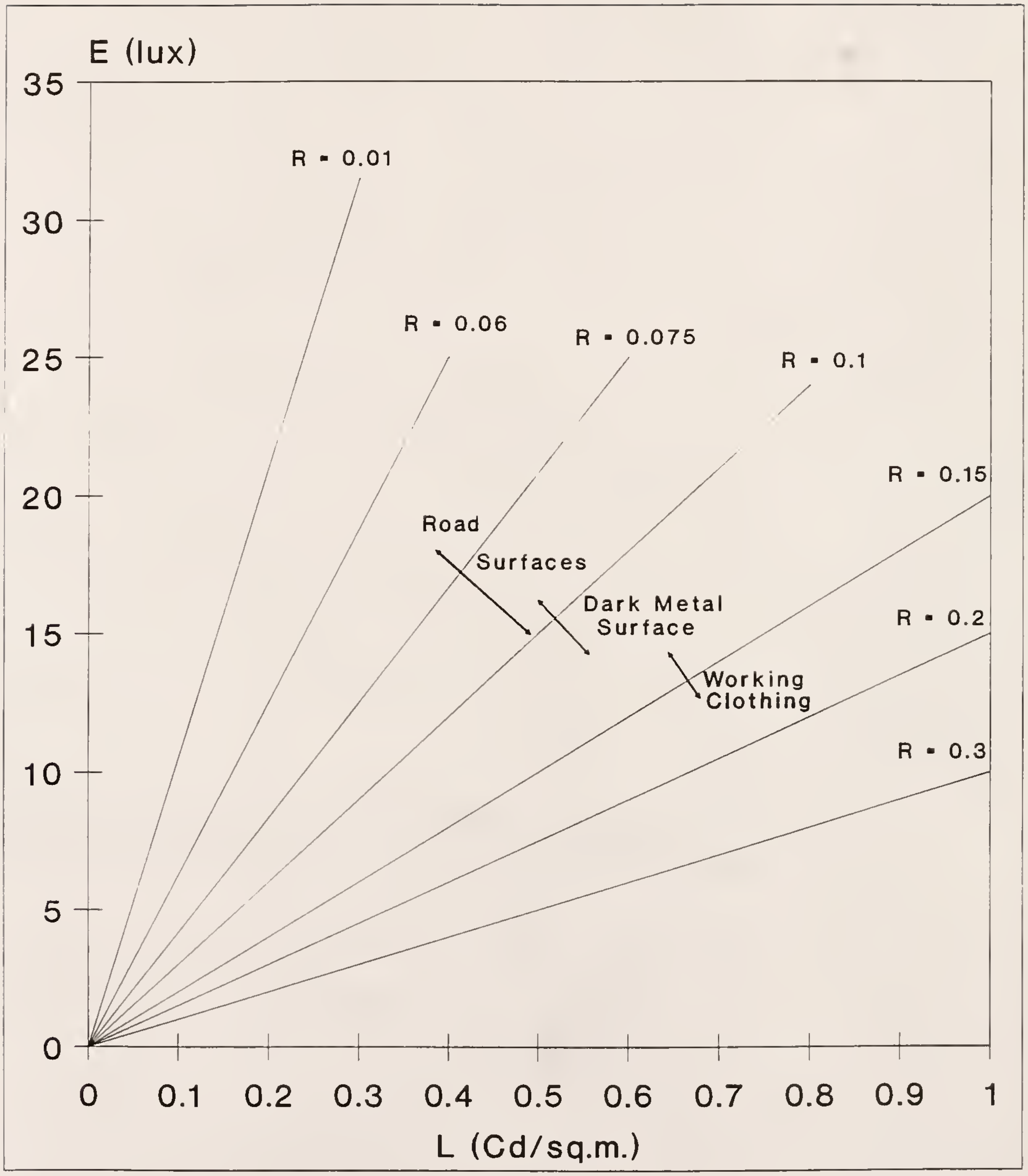


Figure 2.3 Relation Between Illuminance (E) and Luminance (L) for the Surface of Diffused Reflectance <u>Source</u>: Ref. 13

which reduces the perceived contrast of a complex target to threshold and thereby establishes its visibility. CIE published report No. 19/2 describes a mathematical model for influence of lighting parameters on visual performance (15). In the model, a term visibility index is defined as

$$VI = (C.RCS.\ DGF.TAF)/0.0923$$

where

C = contrast

RCS = Relative Contrast Sensitivity

DGF = Disability Glare Factor

TAF = Transient Adaptation Factor

Physical variables required to determine these factors are: 1) luminance of task, 2) luminance of the background around the task, 3) task size (in angular minutes), 4) age of observer, and 5) veiling luminance. All the above described factors, except TAF, can be determined by these variables. Since research pertaining to quantifying TAF is limited and available evaluation data is also not enough, TAF is usually disregarded during calculations. Sometimes, however, its value is assumed between 0.97 and 1.0.

Effect of Human Factors

Human vision and perception adds another dimension to the complexity of illumination problem Understanding various human factors including physical, physiological and psychological factors is crucial to evaluating its effect on productivity and performance under suitable lighting conditions. In addition, issues of nighttime accidents and safety of crew and motorists also become important, especially during nighttime highway construction. Various

physical and psychological considerations, and effects of human vision on perception and safety are discussed in detail in following sections.

Among several visual functions and physical considerations, Henderson and Burg indicated that adaptation and glare sensitivity are presumed to be of direct concern in night work (16). The primary reason is attributed to their influence on other visual functions necessary in night driving and night work such as static visual acuity. These factors in addition to varying with the individuals, also depend on environmental considerations.

Adaptation

Adaptation is defined as a process of changing sensitivity of visual system to light in order to detect the faintest signal. Sensitivity increases under reduced illumination (dark adaptation) and decreases under increased illumination (light adaptation). Schmidt distinguished three levels of adaptation corresponding to photopic (daytime), mesopic (twilight), and scotopic (night) vision (17). The mesopic range, in which the illumination level varies from 1.0 to 13.7 cd/sqm, is of primary interest in nighttime work and driving. Transient adaptation is a phenomenon associated with reduced visibility after viewing a higher or lower luminance than that of the task. Recovery from transient adaptation usually takes a fraction of a second; however, for slow recovery (i.e., more than one second) especially in the case of a brightly lighted exterior, it can be a problem (8). During the process of transient adaptation recovery any recognition task needs higher contrast. The greater the change in luminance level is, the greater is the additional contrast necessary for recognition.

Recovery from transient adaptation usually results in momentary losses in visibility. A research study of the losses in visibility for nighttime highway lighting conditions revealed that at low luminance levels, sudden increases produces losses in visibility equivalent to those

found at higher levels (18). However, at low luminance levels, sudden decreases caused smaller losses than those observed at higher levels.

Glare sensitivity

Glare is usually classified in two categories: 1) disability glare and 2) discomfort glare. Disability glare, which is also known as veiling luminance, is caused by scattering of incident light by the ocular media. Because of this scattering every luminous point in space acts as a source of stray light for nearby points resulting in mixing of images on retina and reducing contrast. Discomfort glare, which is also called as direct glare, is a sensation of annoyance caused by viewing a high brightness source directly. Discomfort glare can be reduced by decreasing the luminance or area of light source or by increasing the background luminance around the source.

A study on glare recovery reported a progressive deterioration in glare recovery ability with advancing age and the rate is greatly accelerated after age 40 (19). In general, recovery from the effects of glare depends on the retinal area involved, its previous adaptation level, intensity of the glare, exposure time, color of the glare source, accompanying changes in pupil size, and visual health of the individual (20). In addition to its direct physical effects, discomfort glare encountered in night driving and night work may be an important factor in inducing fatigue and drowsiness, even if the glare is not strong enough to directly reduce visual efficiency.

The method of evaluating disability glare was suggested by Holladay (21). The effect of glare is quantified by an equivalent uniform luminance that describes the effect of the stray light in the eye–lowering the contrast. The veiling luminance represents the illumination at the eye due to glare sources and is the equivalent uniform luminance superimposed over the

entire visual field. To evaluate its effect, this value can be compared with the average luminance or the adaptation luminance. In order to specify limits of source luminances to avoid disability glare, various studies have been undertaken. One such recommendation from CIE for mining applications accepts a value of 3000 cd/sqm in miner's visual field as permissible (13).

In order to quantify and measure discomfort luminance, Luckiesh and Guth defined a threshold luminance just necessary to cause discomfort (22). This threshold is called the borderline between comfort and discomfort (BCD). Investigations revealed that BCD luminance increases linearly with the increase in background luminance for interior spaces and night driving. Figure 2.4 shows the effect of glare source size on BCD luminance, which decreases with the increase in size of glare source at different of background luminance(8).

As a subjective appraisal of discomfort glare in roadway lighting, the CIE has suggested a relative index known as Glare Control Mark (GM)(23,24). GM provides an ordinal scale indicating the degree of discomfort experienced. The value of GM is related to different glare sensation as follows:

Glare Sensation	GM
Unbearable	GM-1
Disturbing	GM-2
Just admissible	GM-5
Satisfactory restriction	GM-7
Unnoticeable	GM-9

The words of sensation are not intended to indicate an absolute level of glare; however, they are used in experiments of CIE. The subjective appraisal of the glare and the asso-

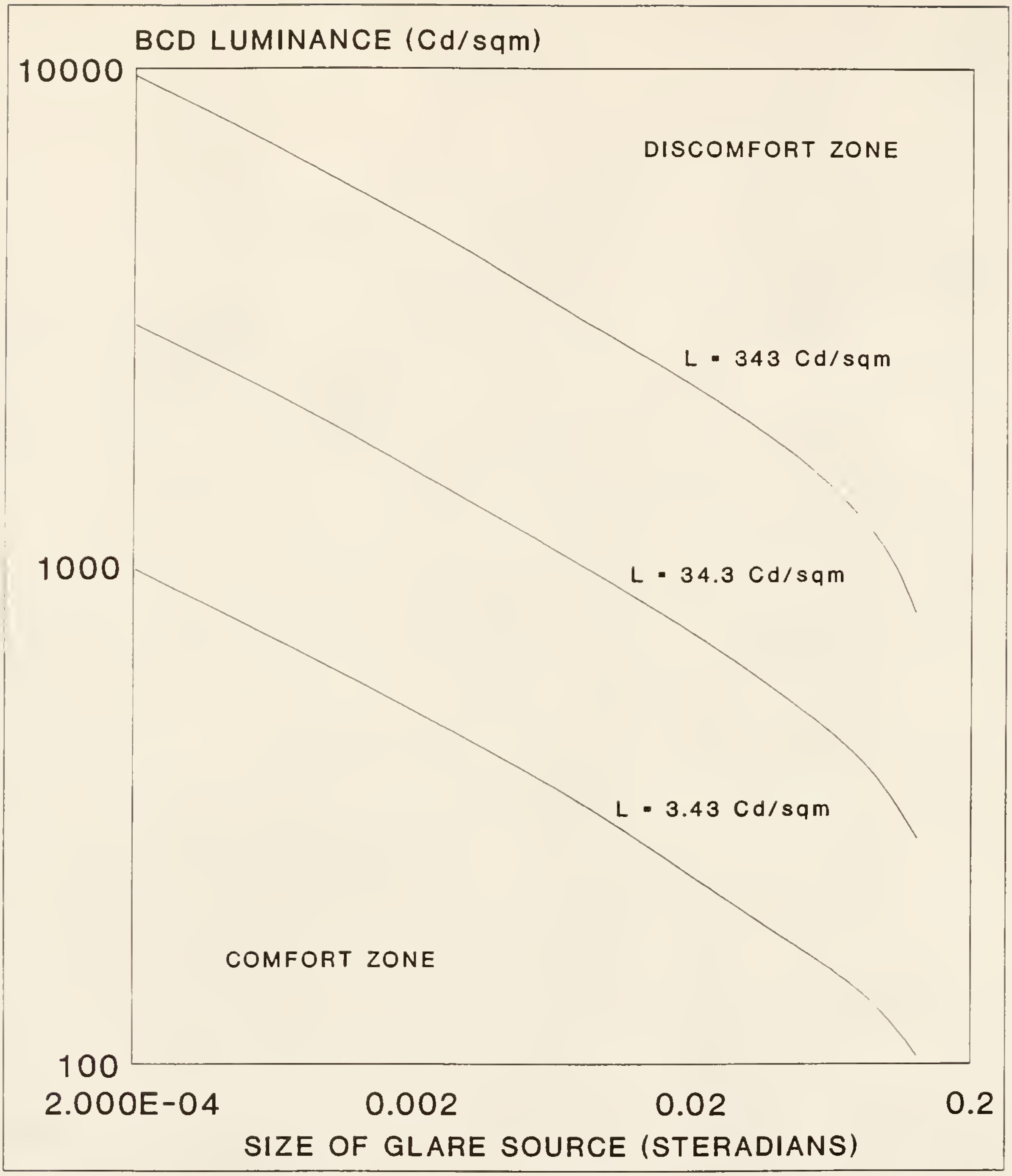


Figure 2.4 Effect of Glare Source on BCD Luminance at Different Levels of Background Luminance <u>Source</u>: Ref. 8

ciated value of the GM depends on the photometric and geometric characteristics.

A visual comfort probability (VCP) system has been developed to evaluate acceptability of lighting systems and its environment as being comfortable (25). VCP indicates the ratio of observers accepting the system as comfortable to the total observers when observers are subjected to direct glare from the luminaries. Table 2.1 gives conditions based on consensus for which discomfort glare is not a problem.

Table 2.1 Conditions for Discomfort Glare Acceptability

Angle above Nadir (degrees)	Maximum Luminance (cd/m^2)	Visual Comfort Probability (VCP)	Uniformity Ratio (Maximum/Average Luminance)
45	7710		
55	5500		
65	3860	70 or higher	5:1 or less
75	2570		
85	1695		

<u>Source</u>: Ref. 25

In a study of workers' sensitivity to glare Guth found that mining workers are exposed to high degrees of glare, especially from the lighting equipment on machines (26). As a result they are less sensitive to glare and select higher BCD luminances.

Physical and Psychological Considerations

Determining adequate lighting not only requires physical considerations including task visibility but is also affected by various psychological issues. Several studies were conducted to examine the "comfortable" level of illuminance and observer's preferences. Bodmann found that judgement of optimum illuminance increased with age and task contrast (27). A general trend of increased satisfaction with higher illuminance and decrease in satisfaction at very high levels of illuminance was also observed and confirmed by Boyce (28).

Some researchers have also studied the psychological effects of uniformity of light. In general, one sees better with more uniform light distribution in the visual field. Tuow found in an experiment that the subjects preferred uniformity ratio of 3:1 for higher illuminances (500 lx) whereas for lower illuminances a ratio of 2:1 was preferred (29).

Research has also been conducted on human factors and behavioral studies to examine behavioral changes with lighting levels. Taylor concluded that lighting affects spatial orientation of people and when navigating around a barrier, people tend to follow the direction of higher illuminance (30). Another study investigated subjects' preferences as related to brightness and found that subjects preferred to work in the areas facing or near bright areas (31).

Lighting was also found to have a psychological affect on people concerning their activity level and attention not directly related to seeing and vision. Activity level seemed to be increased with higher illumination and similarly reduced with low illuminance levels. Light was found to have an effect on the performance of a reaction time task (32).

Safety and Accidents

The need to conduct highway maintenance and reconstruction creates legitimate safety concerns, for both the workers and the drivers. The issue of safety during nighttime construction has been addressed in several research reports. One such study listed some limitations of nighttime construction influencing safety, which included (1):

1) Light conditions of the environment and visibility;
2) Glare and disorienting effects of sudden bright lights;
3) Reduced level of alertness on the part of the work force due to working alternate shifts and fatigue;
4) Physical condition of drivers such as drowsiness, sleepiness, fatigue and overdrive, etc.;
5) Higher speeds on the highways due to decreased traffic volumes; and,
6) Greater incidence of drivers under the influence of alcohol and other substances.

According to a California Department of Transportation (DOT) report nighttime construction accounted for 60 percent of the injuries/fatalities sustained in highway workzones (33). Most worker fatalities (and major injuries) are related to errant drivers causing these accidents. One study of psychological behaviors pointed out that most confident drivers tend to "overdrive" the illumination afforded by the headlights of the vehicle (34). With darkness, various recognition functions such as activity, sensitivity to contrast and ability to perceive objects degrade rapidly.

Standing Committee on Highway Traffic Safety of the American Association of State Highway and Transportation Officials (AASHTO) conducted a study on workzone accidents

and found nighttime accidents were more severe than daytime accidents (35). The study concluded:

> workzone fatal accidents concentrate in rural areas and the vast majority of all workzone accidents and injuries are concentrated in urban areas. . . . Accidents occurring in workzones are generally more severe producing more injuries and fatalities than the national average for all accidents . . . more than two-thirds of all accidents in the workzones occur in daylight. The accidents occurring in darkness are far more severe. Nighttime accidents account for more than half the fatal accidents and more than their proportionate share of injury accidents. About half of all workzone fixed object accidents occur in darkness. (35, p.16-17)

In an effort to reduce night accidents on a street, a four-year study was conducted and illumination levels were maintained at a design level of 15 lx (36). Accidents at night were found to be reduced due to improved illumination of the street. A study undertaken by the Illuminating Engineering Research Institute gathered data from six metropolitan areas to study optimum illumination levels and uniformities from the standpoint of accident reduction (37). Although the study did not conclude that higher illumination levels necessarily reduce accidents, it also did not reject the possibility. The findings are summarized in Table 2.2. In general, streets with little or no illumination had substantially higher night-day accident ratios.

Table 2.2 Relation Between Illumination and Night/Day Accident Ratio

Illumination Level (in fc)	Night-Day Accident Ratio	
	All Accidents	Injury - fatal
0.3 - 0.6	1.07	1.40
0.8 - 1.1	1.69	1.93
1.3 - 1.5	1.65	1.85
0	2.37	3.53

<u>Source</u>: Ref.37

Performance and Productivity

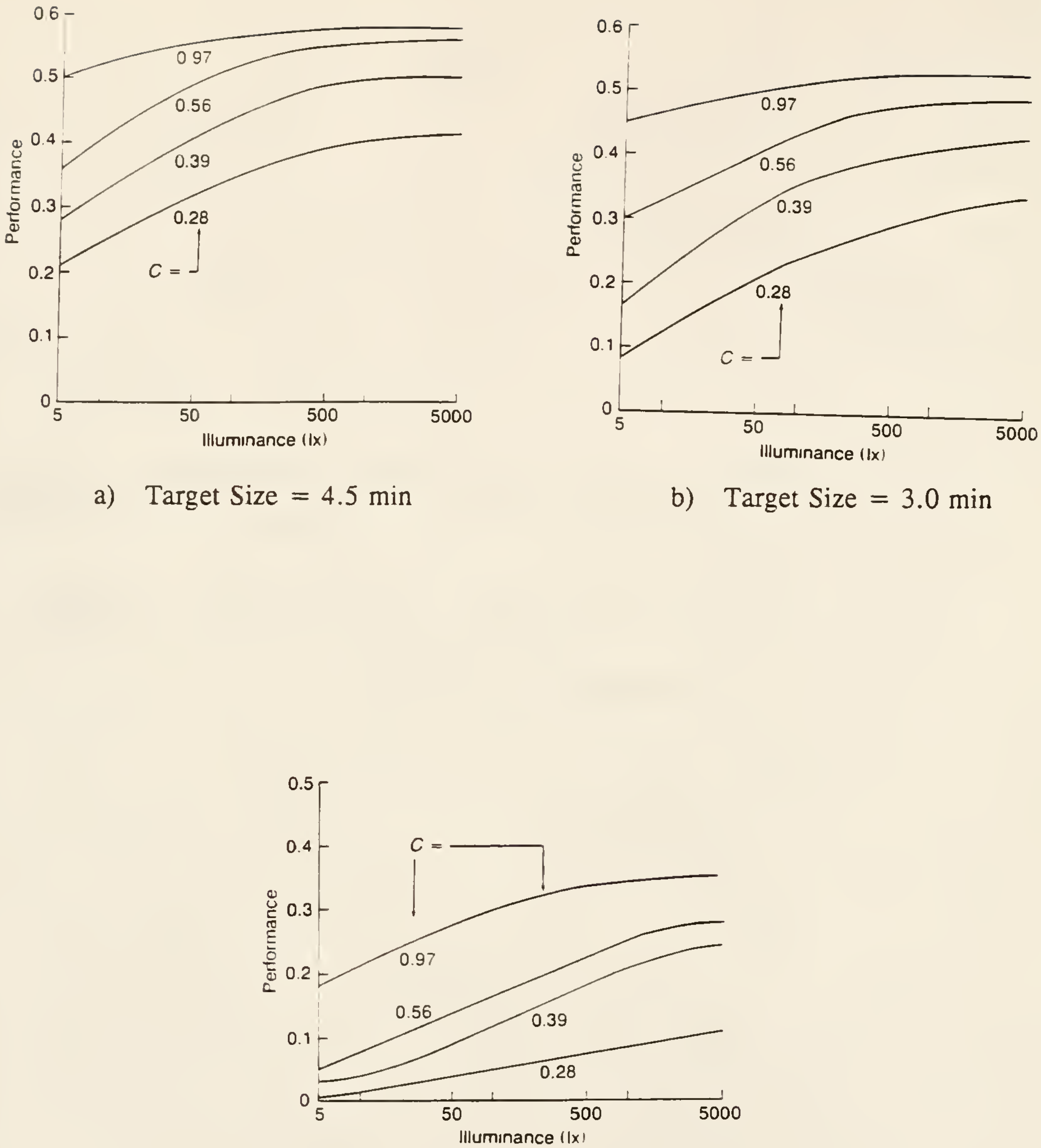
The IESNA has recommended illuminance levels for various tasks for nearly eight decades. The objective of which has been to maximize productivity in terms of greater speed and accuracy while limiting the cost of lighting equipment. It is recognized that, in general, visual systems perform better at higher illuminance levels (8).

Several studies have been conducted imitating realistic tasks to determine how illumination affects performance. One of the earlier studies indicated that as background luminance increased, performance measured in terms of speed and accuracy, increased (38). This increase had a trend of diminishing returns which was more visible for high-contrast, large targets than for low-contrast, small targets. Figure 2.5 shows the trend for varying contrast and target sizes.

Rea and Smith performed several studies on more realistic tasks under different levels of illumination (39). In a needle probe experiment, Smith confirmed Weston's findings that performance improved at a decrease in rate, as light level increased to about 940 fc (10,100 lx). He concluded that

> Performance was better with a white background than with a black one under the same illumination. However, for equal luminances or visibility levels, performance for the black background was superior. (39, p.7)

Figure 2.6 shows the results of the study. Other studies conducted by Rea and Smith included experiments involving: 1) proof reading of paragraphs for misspelled words, 2) reading for information taking a reading test, and 3) check value verification (5, 6, 40). It was found by Smith that performance increased rapidly as illumination increased, then it gradually approached to an asymptotic value (39).



a) Target Size = 4.5 min

b) Target Size = 3.0 min

c) Target size - 1.5 min

Figure 2.5 Performance as a Function of Illuminance for Different Task Sizes and Varying Contrast Source: Ref. 8

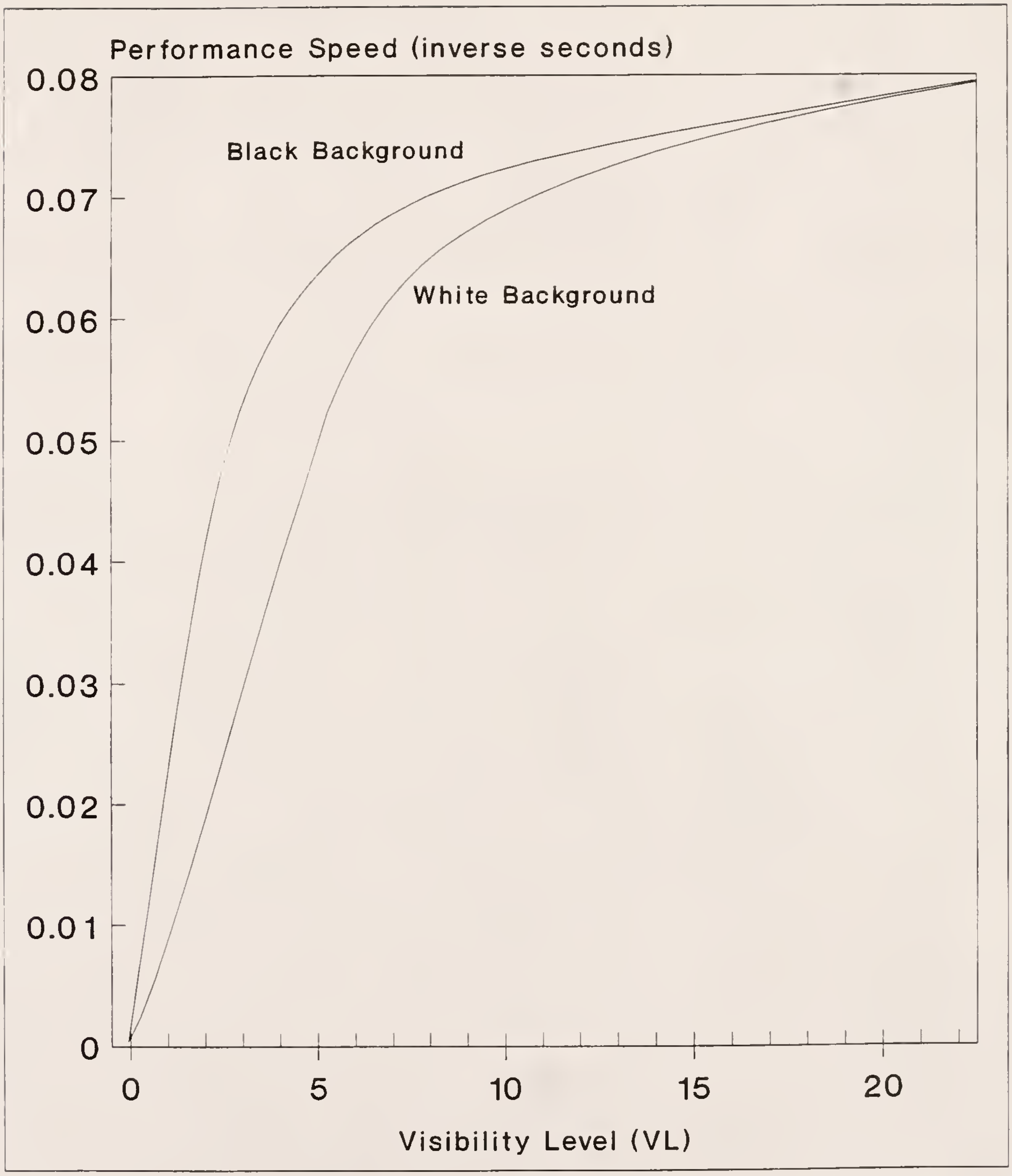


Figure 2.6 Relation Between Performance Speed and Visibility Level

Source: Ref. 39

Lighting Standards and Guidelines

A combination of codes, regulations and standards affect lighting design and the choice of lighting equipment. These include state, national and international codes, local ordinances, and professional and manufacturers standards. The standards and guidelines are intended to provide adequate lighting for various visual tasks, which sometimes are restricted by local ordinances intended to reduce light spillage, restrict illuminance levels, and reduce glare. However, most current lighting standards are largely based on the illuminance recommendations of the Illuminating Engineering Society (IES).

IES Standards.

Selection of appropriate illuminances was suggested by the IESNA following an evaluation of factors affecting visual performance (8). According to the recommendation, illuminances for interiors are provided in the form of general categories and a specific illuminance level from a category is selected based on the weight of certain factors. The ranges of the categories conform to the ones recommended by the CIE which were derived on a consensus basis (41). The factors playing important roles in the selection of a particular level for interiors include: 1) age of the observer, 2) size of the target, 3) contrast of the task, 4) need for speed and 5) accuracy. For exterior, however, fixed values of illuminance levels to be maintained on the task are recommended.

The minimum required illuminance levels from safety considerations are shown in Table 2.3. These levels are regarded as regulatory minimum levels and to maintain these values, higher initial levels must be provided as required by the maintenance conditions (8).

Table 2.3 Illuminance Levels for Safety

Hazards Requiring Visual Detection	Illuminance Levels for Normal Activity Level (in fc and lx)	
	Low	High
Slight	0.5 (5.4)	1 (11)
High	2 (22)	5 (54)

Source: Ref. 8

Illuminance levels are also recommended to provide a guide for efficient visual performance for various activities. Table 2.4 summarizes the recommended levels for construction activities along with uniformity ratios, which are similar to the ones recommended by CIE–Guide to the Lighting of Exterior Working Areas (42).

Table 2.4 Recommended Levels for Uniformity Ratio and Construction Activities

Activity	Illuminance Levels in fc (lx)	Uniformity Ratios
General Construction	10 (108)	1 to 5
Excavation Work	2 (22)	1 to 5

Source: Ref. 8

The recommendations of the IES are approved as American National Standards by the ANSI Board of Standards. There are two ANSI standards relevant to construction workzone lighting: 1) RP-7-91, Industrial lighting, and 2) RP-8, Roadway lighting (43, 44). Standards on industrial lighting relate to industrial activities both indoor and outdoor and is in complete agreement with the IES recommendations. The standard related with roadway

lighting provides recommended maintained luminance and illuminance values and uniformity ratios for various types of roadways.

OSHA Standards.

Occupational Safety and Health Administration (OSHA) has specified minimum illumination intensities for construction and related areas. These values, taken from ANSI standards and IES recommendations, are included in OSHA Safety and Health Standards (29 CFR 1926/1910) and are presented in Table 2.5 (45). For other areas or operations not covered in the table, refer to the American National Standard A11.1-1965, R1970, Practice for Industrial Lighting, for recommended values of illumination.

Section 75 of the Code of Federal Regulations (CFR) number 30 provides detailed illumination standards for the mining industry (46). According to the code 0.06 foot lambert of luminous intensity is required on the surfaces that are in a miner's normal field of vision. For self propelled machines, the illuminated surface which is within 10 ft of the front and the rear of the machine should have a luminous intensity of not less than 0.06 foot lamberts. In addition to illumination level in working places, the code also addresses the issues of lighting fixtures, methods of measurement, and mining machines and cap lamps requirements. Table 2.6 provides the proposed regulations for illumination requirements of various equipment such as – draglines, shovels and wheel excavators (47). Figures 2.7(a) and 2.7(b) explain the method of measurement of luminous by intensity direct measurement and by averaging method, respectively (46).

Table 2.5 Minimum Illumination Intensities for Construction Industry

Area or Operation	Illumination Intensity (in fc)
General construction area lighting	5
General construction areas, concrete placement, excavation and waste areas, access ways, active storage areas, loading platforms, refueling, and field maintenance areas.	3
Indoors: warehouses, corridors, hallways and exit ways	5
Tunnels, shafts and general underground work areas: (Exception: minimum of 10 foot-candles is required at tunnel and shaft heading during drilling, mucking and scaling.)	5
General construction plant and shops (e.g., batch plants, screening plants, mechanical and electrical equipment rooms, carpenter shops, rigging lofts and active store rooms, barracks or living quarters, locker or dressing rooms, mess halls, and indoor toilets and work rooms).	10
First aid stations, infirmaries, and offices	30

Source: Ref. 45

Table 2.6 Proposed 30 CFR Regulations Illumination Requirements for Draglines, Shovels, and Wheel Excavators

Location	Average Illumination Intensity (fc)	Uniformity Ratio
1. All areas 20 ft in all directions from the main frame	5.0	10/1
2. All work or travel areas beneath the main frame	5.0	10/1
3. Interior areas except operating cabs	10.0	10/1
4. Exterior walkways, catwalks, and ladders on main frame and boom	5.0	10/1
5. Interior walkways	10.0	10/1
6. Area beneath boom from 20 ft from main frame to furthest point equipment can excavate or discharge material	1.0	10/1

Source: Ref. 47

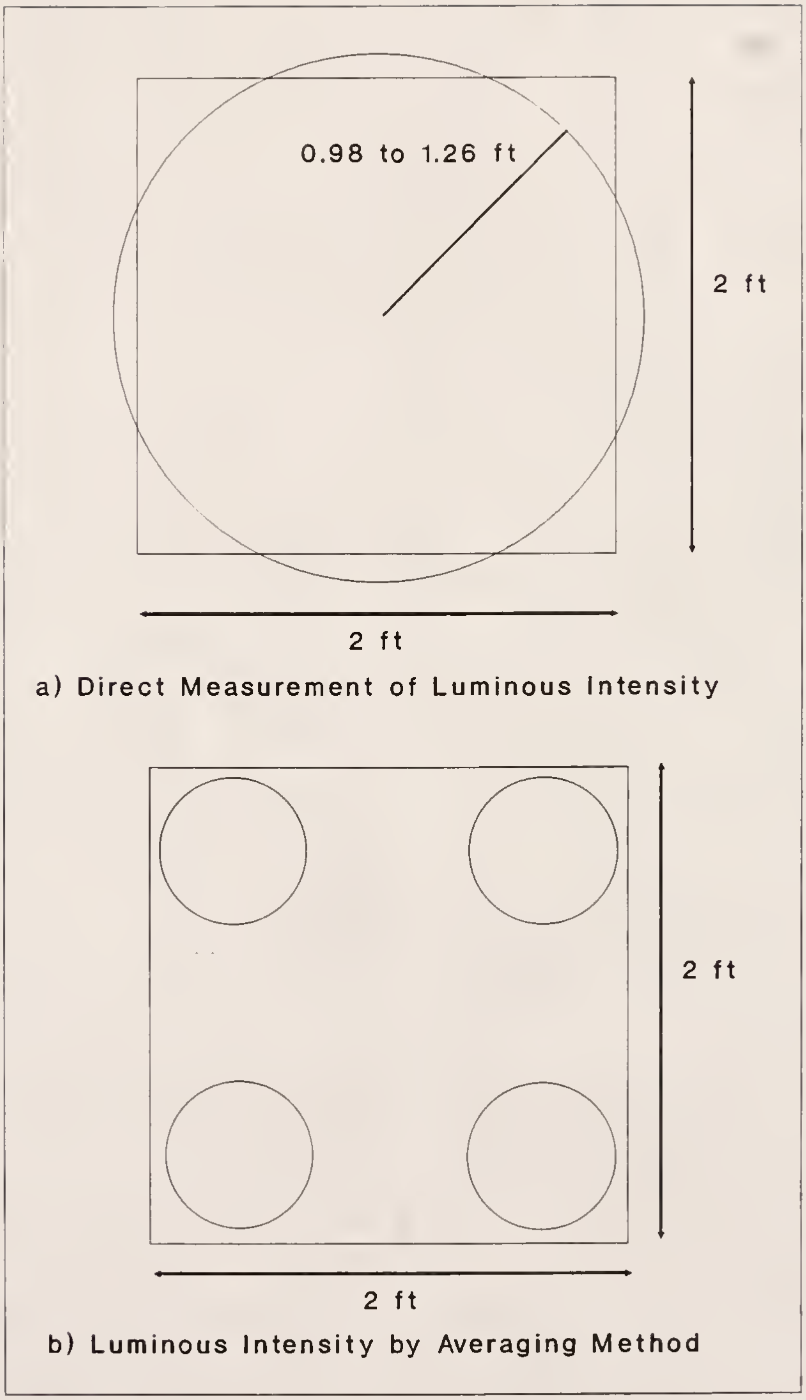


Figure 2.7 Methods of Measurement of Luminous Intensity

Source: Ref. 46

State DOT's Specifications

As evident from construction literature, nighttime work is common on many highway projects across the country particularly in Florida and California. Questionnaire survey results showed that most of the highway agencies, with a few exceptions, do not have detailed specifications pertaining specifically to nighttime construction. A summary of these results by state are presented in Table 2.7. The states having detailed lighting specifications concerning nighttime construction include — California, Connecticut, Florida, Maryland, Michigan, North Carolina and Virginia. For workzone lighting such specifications mention only the minimum illumination intensities required (e.g., 5 fc, etc.), which is presumed to be adequate for all construction activities. In addition to this, some specifications require the contractor to provide sufficient light for safety of personnel and quality of work. As a result, most of the contractors develop their own systems. Considering project variations, and few or no standards to go by, workzone lighting has little uniformity.

The FDOT standard specifications devotes a section 8-4.1 to nighttime construction only. It requires the contractor to furnish and place all lighting facilities on site and maintain light intensity of 5 fc minimum at all times. Lighting may be accomplished by the use of portables, standard equipment lights, street lights, etc. The contractor is also required to submit a lighting plan at the Preconstruction Conference showing the type and location of lights to be used (48). Similar specifications are included in the standards of Illinois and New York highway agencies. In California, the minimum illumination intensities are established by the California Division of Occupational Safety and Health Construction Safety Orders. Virginia Department of Transportation requires the contractor to provide a minimum

Table 2.7 Summary of Provisions for Lighting Requirements and Guidelines for Various States

Name of the State	Brief Description of the Provisions for Lighting
Connecticut	Paver - 6 fluorescent and 4 flood lights; Roller - 2 flood and 2 spot lights
Florida	Min 5 fc
Maryland	Min 20 fc (215 lx); 30 ft (9 m) high tower; beam angle < 60 deg
Michigan	Paver - min 10 fc, 6 ft tower with 5 lights; 100-200 ft behind Roller - min 10 fc; 4 ft tower with 4 lights; 50-100 ft front & behind Workzone - min 10 fc
North Carolina	Tower - 30 ft high, lumen 50,000-460,000, min 20 fc, angle < 60 deg Machine - 13 ft high, lumen range 22,000-50,000, min 10 fc
Virginia	Min 50 fc in 15ft x 15ft area and 5 fc in the corners

of 50 fc of light for areas of approximately 15 ft by 15 ft with a minimum of 5 fc in the corners of the area (49).

The State of Connecticut has recently included a contract provision "Lighting for Night Paving" in several nighttime paving projects. The provision addresses lighting requirements for the paver and roller only to illuminate the work area and equipment. The contractor is responsible to furnish, mount and maintain all the required lighting, which is inspected by an engineer for its adequacy prior to allowing a nighttime paving operation to commence or continue. Description of guideline for equipment is as follows:

PAVER–

Fixture Type	Quantity	Remarks
Fluorescent, twin 48" HO	3	Mount over screed area
Fluorescent, twin 48" HO	3	Mount over auger
PAR 38 15W Flood	4	Aim 25-50 ft behind paver

ROLLER–

Fixture Type	Quantity	Remarks
QPAR64 1000W Flood	2	Mounted above roller
QPAR64 1000W Spot	2	Aim floodlights 100 ft in front of and behind roller. Aim spotlights 200 ft in front of and behind roller.

According to the provision, the contractor is responsible for providing portable diesel generators on rollers and pavers to adequately furnish 120v electric power to operate the specified lighting equipment. Design and fabrication of bracket and hardware should be done by the contractor to mount light fixtures and generators to suit the configuration of the rollers

and pavers. The issues of glare to traffic, obstruction to traffic, safety codes and adjustable mounting are also briefly mentioned in the contract provision. The cost for providing any lighting is not measured for payment separately.

A similar special provision is also included by Maryland State Highway Administration for nighttime pavement repairs. According to the provision, if existing light levels are below 20 fc (215 lx) over the construction area, supplemental or flood lighting should be utilized. The contractor is required to submit a situation plan showing the locations and aiming of the floodlights. The lighting system will be checked for proper aiming, positioning, level and uniformity of illumination and any hazard to maintenance of traffic. Other specifications as outlined in the special provision include

Illumination level:not less than 30 ft (9 m) for directly influenced traveled roadway

Mounting height: not less than 20 ft (6 m) for indirectly influenced traveled roadway

No additional payment is made for the contractor utilizing nighttime construction. All the material and equipment for lighting is furnished by the contractor and remains the contractor's property.

Michigan Department of Transportation also has included a special provision for lighting for night paving. The provision outlines lighting arrangements for paver, roller and general workzone lighting. The summary of nighttime paving operation and requirements as addressed by the provision is as follows:

PAVERS–

- illumination level on and around paver should be a minimum of 10 fc.
- a tower with minimum height of 6 ft should be mounted on the paver holding five lights.
- one light on the tower should be facing forward and four lights facing toward the new mat being laid.
- area behind the paver should be lighted up to 100 ft to 200 ft.

ROLLERS–

- each roller should be equipped with four headlights–two facing each direction of travel.
- a tower with a minimum height of 4 ft should be mounted on the roller equipped with four lights.
- two lights of the tower should face each direction of travel lighting the area 50 ft to 100 ft.

WORKZONE–

- auxiliary lighting should be provided for the entire paving operation.
- each light should be a minimum of 500-watt quartz.
- ramps, gore areas or areas of extensive hand work should have separate supplemental lighting of 500-watt quartz minimum.

The State of Michigan has also included a supplemental specification for nighttime casting of superstructure concrete. One section of the specification deals with the lighting and specifies an average intensity of 10 fc minimum to be maintained on the work area. Lighting for night paving is paid as lump sum unit.

State of North Carolina has included a section describing portable lighting which is used for compliance with the standard specification section on night work requirement for artificial lighting. The department requires the contractor to present a lighting plan on standard size roadway plan sheets. Such a plan must clearly show the location of all lights necessary for every aspect of work to be done. The section deals with tower and machine lights separately and can be summarized as below:

TOWER LIGHT–

- height of tower light should be 30 ft.
- light should consist of mercury vapor, metal halide, high pressure or low pressure sodium fixtures.
- each fixture should have a minimum output of 50,000 lumens and combined output of all fixtures should not exceed 460,000 lumens.
- should provide an average maintained horizontal illuminance greater than 20 fc over the work area.
- main beam of the light should not be aimed higher than 60 degrees above straight down.

MACHINE LIGHT–

- mounted on supports attached to construction equipment at a height of approximately 13 ft.
- each fixture should have light output between 22,000 lumens and 50,000 lumens.
- electrical grounding of generators to the frames of machines should be in accordance with National Electric Code (NEC)
- lights should be able to provide a minimum level of 10 fc around the equipment.

- these lights are in addition to conventional equipment headlights.

In addition to light specification there is a small section briefly addressing construction methods and lighting arrangements. Payment for the lighting provided by tower and equipment lights is made at the contract lump sum price for "portable lighting."

Current Practices

Nighttime Work

In a study of construction practices related with nighttime pavement, at various airports with asphaltic concrete, it was found that certain clauses dealing with construction lighting were included in the contract specifications (50). According to the specification, the contractor was required to install, maintain and relocate temporary light to illuminate the working areas during the hours of darkness when overlay operations are in progress. The lighting equipment was to be trailer-mounted units, each with four 1000-watt metal halide or high pressure sodium lights on a winch-lift telescopic mast. The contractor was to maintain an average illumination level of 5 fc throughout the working area and should submit isolux curves or charts showing the pattern of lights. Levels were to be calculated and measured in accordance with standards of IES current practice. In addition, all paving machines, rollers, distributor trucks and other equipment (except haul trucks) were to be equipped with artificial illumination sufficient to safely complete the work.

Minimum illumination level was to be 5 fc and was to be maintained in the following areas:

1) An area 25 ft wide and 12 ft long immediately behind the asphalt spreader during the

1) An area 25 ft wide and 12 ft long immediately behind the asphalt spreader during the operation of the machine.
2) 12 ft wide by 30 ft long area immediately in front and back of all rolling equipment.
3) 12 ft wide and 12 ft long at any point where tack coat is being placed prior to placement of the hot mix asphalt overlay.
4) 12 ft wide by 20 ft long immediately in front of the cold milling machine.
5) 12 ft by 30 ft long immediately in front of the heater scarifier and heater planing machine.
6) 12 ft wide by 30 ft long in front of the rubber asphalt distributor and spreading equipment.
7) 12 ft wide by 12 ft long at any point where joint sealing operations are in progress.

This level of illumination can be obtained with four 1000-watt metal halide floodlights at 30 ft mast height aimed at 60 degrees and placed at approximately 200 ft centers along each edge of the runway (50).

An illumination case study of a stripping shovel by Faux suggested that an illumination intensity level of 10 fc on the workface and around the machine was found satisfactory by the operators for visual tasks (47). In the study it was recommended that a 20 ft area on all sides of the machine and 100 ft in the front should be illuminated with minimum 10 fc intensity. To provide good color rendition a combination of metal halide as the high intensity discharge (HID) source and tungsten halogen as the incandescent type was utilized and was found to be providing a highly satisfactory quality of light for the application.

For widening and redecking a six-lane bridge in Maine, lighting was provided by trailer units supporting four 1000-watt sodium vapor fixtures (51). Several smaller two-lamp

units were used as necessary for supplemental lighting. For a paving operation in New Jersey, auxiliary generators of 3500-kw low RPM 4 cycle were used to take care of additional lighting (52). On the same project, rollers were equipped with five 300-watt all weather bulb clusters at the front and back; whereas, on the spreaders, due to vibration, four heavy duty bulbs of 400-watt sealed beam clusters were used. At asphalt plant site six 1500-watt wide angle mercury vapor lights were used at strategic locations. These lights were sealed and had highly polished reflectors.

According to one study on a project in Denver, Colorado, insufficient lighting was a problem (53). It was found that existing light, about 1 fc, produced from light standard is not sufficient for construction procedures. For crack filling, 500-watt spot lights mounted approximately 10 ft high on each corner of the crack filling machine were used. The work area was measured to be 36 fc with light meter and appeared to be sufficiently lit for the workers to work without any restraint. This conformed to the IES minimum light levels requirements for similar tasks. The paving machine was equipped with five high intensity lights, two on each side of the machine and one in the center, and the lighting was found to be adequate. The roller used only one spotlight along with the headlights, which did not seem to be adequate. Lighting systems attached to the equipment worked well when the crew doing the hand work had control over the speed of the vehicle such as the crack filling operation, however for paving because of its fixed speed such a system did not work well.

In a project in San Diego, California, six Allmand maxi-lites were placed on the perimeter of the section being paved (50). The rollers had their own headlights to provide increased visibility to the area. In most of the other places, four 1000-candle power lamps were used to maintain the required minimum illumination level of five footcandles, which was

obtained with four 1000-watt metal halide floodlights at 30 ft mast height aimed at 60 degrees.

Lighting Sources and Equipment

To obtain information concerning current construction workzone lighting practices, various lighting manufacturers and suppliers were contacted. Although most manufacturers did not indicate substantial construction lighting experience, it was, however, noted that incandescent and HID types of sources are most commonly used in construction workzones. In Florida most of the construction sites were found to be equipped with four 1000 watt metal halide light towers.

Incandescent lamps include tungsten halogen lamps and HID includes mercury vapor, metal halide and high pressure sodium. Each lamp has its respective advantages and disadvantages. Incandescent lamps have an advantage of lowest initial cost, instant on, no ballasts, natural day light color, good light aiming control and very low lumen depreciation. However, low lumen output and short lamp life are some of the drawbacks with incandescent lamps in addition to their high surface temperature.

In the HID group, mercury vapor lamps also are vibration resistant and fast restrike time. They also have longer life; but, lower lumen output and high lumen depreciation are some of the drawbacks. Metal halide lamps, one of the most commonly used for flood lighting purposes, are known for their good color rendition and high lumen output. Although they have long restrike time and medium lamp life, they are good for overall lighting. Restrike time is relatively faster with high pressure sodium lamps, however their higher initial cost and insufficient color rendition do not make them very popular for construction lighting.

Other advantages of high pressure sodium include: high lumen output, low lumen depreciation, reduced glare and total system cost. Table 2.8 provides a summary of ratings of various lamps used for construction lighting (8).

In general, HID lamps have longer lamp life and efficacy (lumens per watt). There is a time delay and restrike time when the lamps are first started. Typically due to their high efficacy, less luminaries are required than for an incandescent type of lighting. In addition, because of their rough service capability and better vibration handling, HID lamps are considered suitable for highway workzone lighting.

Usually for highway construction lighting HID lamps are grouped in sets of two or four lamps. These luminaries are typically mounted on portable trailers and are accompanied by generators. The luminaries are commonly narrow beam and used for area lighting or flood lighting. Incandescent lamps, however, are usually mounted on highway construction equipment and used for spot lighting of the tasks.

Field Investigation

A number of field trips were made to investigate the current FDOT nighttime highway construction and maintenance practices. The selection of projects was based on their geographical location and diversity. In selecting projects in Florida not only was an effort made to select representative kind of typical highway projects, but care was taken to avoid repetition and a variety of projects covering nearly all the operations were chosen.

A field review form was prepared to record all relevant information as observed on site. The form included pertinent information such as: project information and location; tasks in the operation, their importance, reflectance and distance

Table 2.8 Technical Information and Rating of Light Sources

Light Source	Lumen Output Per Lamp	Efficacy (Lumens Per Watt)	Life (hrs)	Color Acceptability	Degree of Light Control	Maintenance of Lumen Output
Incandescent - Tungsten Halogen	Fair	Low (24)	Low (2,000)	High (Day Light White)	High	Fair
Mercury Vapor	Good	Fair (63)	High (24,000)	Fair to Good (Medium White)	Fair	Fair
Metal Halide	High	Good (110)	Good (10,000)	Good (Bright White)	Good	Good
High Pressure Sodium	High	High (140)	High (24,000)	Fair (Soft, Orange)	Good	High
Fluorescent	Low	Fair to Good (85)	Fair (7,500)	Fair to High (Daylight White)	Fair	High

Source: Ref. 8

of seeing; general lighting information, lighting equipment, and configuration; quantity of light and illumination levels: uniformity, direction and glare of light; and general information about workers and power sources.

During field reviews several projects with different nighttime operations were visited. This included projects in rural, urban and semi-urban environment on limited access, primary and other types of roadways. Various types of operations included: replacing concrete barrier wall to separate traffic from workzone; asphalt concrete paving of intersection; in-situ concrete construction of bridge deck; excavation, filling and embankment construction; and milling, repaving and marking of limited-access highway. A list of FDOT projects and field observation forms are included in Appendix A.

Various tasks were identified related to all the observed operations. Other information such as–background reflectance, importance and speed required, and seeing distance for the tasks were collected. To provide common lighting visually most difficult and fatiguing tasks were also identified in each operation. Most of the observed tasks had low or medium background reflectance owing to low reflectivity of the pavement and other concrete and soil structures. Importance, speed and accuracy of the tasks also varied from low for excavation to high for paving and finishing works. Seeing distances of the tasks were categorized into four main categories: 1) less than one ft, 2) one to five ft, 3) five to 15 ft, and 4) more than 15 ft.

For construction lighting, equipment mounted lights, portable light plants and their combinations were most commonly used. Some equipment such as pavers and rollers were equipped with custom-made retrofit lights. Pavers usually had six or more lights: two lights at the front, two lights at the rear, two lights aiming at the screed, and the rest of the lights

illuminating the sides of the equipment. Compacting rollers and brushing rollers usually had two to four sealed lamps and sometimes additional mounted lights. However, wheel loaders, dump trucks and flat-beds were equipped with manufactured conventional equipment lights. For bridge deck construction at Fort Myers, FL, the crane, conveyor system and screed were equipped with several mounted lights. Milling machine had sealed beam units which were manufactured and installed at the factory. Relatively stationary workzones were usually supplemented by portable light plants which were also used for general lighting of the area.

Most of the mounted lights were 500-watt tungsten-halogen lamps powered by diesel generators. The generators, in most areas, were installed on the construction equipment. These halogen lights were mounted on custom made brackets and poles and provided sufficient flexibility to change lamp height and aim as desired. Most of the fixed lights were 75- to 100-watt conventional automobile lamps and had fixed aim and light positions. The most common portable light found during field reviews was light trailer equipped with four HID lamps of 1000 watts each. Trailers were also equipped with diesel generators and 30 ft maximum height adjustable tower. These light plants utilized metal-halide as one of the most common lamps enclosed in a parabolic reflective cover to provide a uniform narrow beam of light. These light towers provided sufficient uniform flood light for the workzone, however, in some instances they also caused severe discomfort glare and sometimes disability

glare to the motorists especially when installed against the moving traffic. For the bridge deck construction project, the concrete barge and chute were illuminated with 1000-watt sodium vapor lamps enclosed in a rectangular reflective covering. Lights on the crane were 1000-watt metal halide lamps spaced at 30 ft and oriented towards the hoist. For the milling-repaving project on I-295, Jacksonville, FL, lights on the milling machine were fixed and oriented to illuminate the critical areas such as the conveyor, milling edge, rear of the equipment and on the sides.

Quantity of light was found to be sufficient for most of the tasks, however, some tasks were not adequately illuminated; reasons for which were attributed partly to the inadequacy of light plants and partly to their improper orientation. Particularly for compacting rollers, lighting was not sufficient and the operator was moving the equipment broadly in a pattern based on the experience instead of visual task. Similarly illuminance levels were not enough for sweeping brush roller and asphalt spreader applying tack coat. The operators essentially moved in a certain predefined pattern and sometimes failed to notice missed spots. For intersection paving and bridge construction jobs also, illuminance levels for hand spreading of mix were less than satisfactory. In most cases, illumination of the general area was found to be adequate, however, in many cases task illumination was not adequately emphasized.

Factors which were observed to evaluate quality of light included uniformity, direction, diffusion, direct and veiling glare. Lighting for nearly all the observed operations was adequately uniform. In milling and repaving operation, uniformity of light was difficult to maintain because of the continuous movement of the operation. Good uniformity was possible with the utilization of well diffused luminaries. Especially for flood light towers, light was well diffused and uniform as compared to equipment mounted lights which provided

more spot and task illumination. Equipment lighting was usually factory installed sealed-beam units.

The direction of lighting was found objectionable in many cases, particularly for tower lighting plants. For replacing barrier walls on I-75, Gainesville, FL, the plant was placed in close proximity of the travel lane facing oncoming traffic, the result of which was nearly blinding disability glare to the motorists. In other cases, light plants were situated at locations creating a shadow zone on the tasks. Because of inappropriate directivity of lights, on several occasions tasks were performed in negative contrast instead of a positive one. Shadows of defects aided their identification. Spotlights mounted on various equipment, in general, had better directivity. Lights on some of the compaction rollers were not mounted high enough, as a result most of the light fell on the wheels instead of the pavement. Spotlights on milling machine were factory installed and had better directivity.

Veiling glare was negligible for all the observed operations because of the low reflectivity of pavement and other construction surfaces. Direct glare to workers was, in general, more common in the case of highway operations than for bridge construction. The problem of glare to motorists was found to be acute for highway operations in which adjacent lanes were opened to traffic. In urban and semi-urban environment, particularly where roadway lights were available, problems of glare were less, due to reduced background contrast. It was noted during field investigation that lighting design and provision was essentially based on the contractor's discretion, and in some cases, little or no thought was given to location, positioning and orientation of the light plants.

Summary

In this chapter an overview of the state-of-the-art of lighting and nighttime construction practices was presented. For organization the chapter was structured in three parts each of them dealing with review of literature, lighting standards, and current practices respectively. Review of literature consisted of extensive survey of basic concepts in lighting, studies pertaining to design procedures, and effect of human factors in determining adequate lighting. The important parameters of visual task were evaluated including illuminance, contrast, and reflectance. Discussion on human factors consisted effect of glare sensitivity, transient adaptation, and other physical and psychological factors on safety, accidents, productivity and performance.

In order to develop useful and consistent guidelines in this study, various existing guidelines and standards were discussed. Among these standards the prominent ones were from IES, OSHA, and specification of various state highway agencies. Current nighttime highway construction practices were also reviewed through field investigation and survey questionnaire. Lighting manufacturers were also contacted to provide information on the presently used lighting systems for construction lighting. In the remaining part of the report model components are discussed and developed followed by development of guidelines.

CHAPTER 3
MODEL COMPONENTS AND THEIR FORMULATION

Introduction

To formulate the model, the model components needed to be determined and described. The fundamental questions were: 1) Which activities will be included in the model and for guidelines? 2) Which independent and dependent factors will be chosen for the model? and 3) How the preliminary levels for highway tasks will be determined? To answer these questions, this chapter has been divided into three parts. Each part separately deals with the identification of typical highway construction activities, determination of factors affecting illumination requirements for a particular task, and development of a non-highway matrix for comparative analysis.

Nighttime construction activities were identified with the help of literature and survey of various state highway agencies. A questionnaire was prepared and sent to agencies nationwide and responses were compiled and analyzed to prepare a list of typical tasks commonly performed at night. In the second part of this chapter from the analysis of literature review, a number of factors were identified. A list of five significant factors were selected from the above list to be used as independent parameters in the model. For comparison with the existing industry standards, a list of non-highway tasks was identified. A SAS dataset was created from this list which is later used in performing statistical analysis.

Nighttime Work Activities

Preliminary Identification

In order to categorize typical highway nighttime work, various highway operations were identified. Interviews with state highway personnel, opinions of various knowledgeable individuals and review of FDOT standard specifications for road and bridge construction resulted in a preliminary list of the most commonly performed highway operations (48). These operations were categorized into highway maintenance and highway construction tasks. Both lists also included activities on bridges, signalization and other highway facilities. A brief description of these tasks is presented in Table 3.1. The tasks in each list represent various operations and activities which are categorized according to their similarities in visual requirements.

Table 3.2 shows some of these task categories, typical operations represented by them, and various activities involved in the operation. Although all the activities in a particular operation (as shown in Table 3.2) may not have similar visual requirements, they are grouped together for practical reasons. Compliance is more realistic if a single lighting standard is specified for one operation rather than a different standard for each activity in the operation. However, the task category representing several operations is based on the similarity of visual requirements of those operations.

Table 3.1 Description of Highway Construction and Maintenance Tasks Performed at Night

Task No.	Maintenance Tasks performed at night	Construction Tasks performed at night
1.	Maintenance of earthwork/ embankment	Excavation - regular, lateral ditch, channel
2.	Reworking Shoulders	Embankment, Filling and Compaction
3.	Barrier Wall or Traffic Separator	Barrier Walls, Traffic Separators
4.	Milling and Removal	Milling and Removal
5.	Resurfacing	Resurfacing
6.	Repair of Concrete Pavement	Concrete Pavement construction
7.	Crack filling	Subgrade stabilization & construction
8.	Pot filling	Base Courses - clay, cement, asphalt
9.	Surface treatment	Surface treatment
10.	Waterproofing/ Sealing	Waterproofing/ Sealing
11.	Sidewalks repair & maintenance	Sidewalks construction
12.	Riprap maintenance	Riprap placement
13.	Resetting Guardrail/ fencing	Guardrail, Fencing
14.	Painting Stripes/ Pavement Markers	Painting Stripes, Pavement Markers, Metal Buttons
15.	Landscaping/ Grassing/ Sodding	Landscaping, Grassing, Sodding
16.	Highway Signing for maintenance works	Highway Signing for construction
17.	Traffic Signals maintenance	Traffic Signals construction
18.	Highway Lighting System - repair & maintenance	Highway Lighting System construction
19.	Bridge Decks rehabilitation & maintenance	Bridge Decks construction
20.	Drainage Structures maintenance & rehabilitation	Drainage Structures, culverts & sewers construction
21.	Sweeping and Cleanup	Construction of other Concrete Structures

Table 3.2 Categorization of Typical Highway Construction Tasks and Operation

Task Category	Type of Task	Activities
Excavation	Regular excavation Subsoil excavation Lateral Ditch excavation Channel excavation	
Embankment	Dry fill method Hydraulic method	
Backfilling	Pipe Culverts Storm Sewers Other Structures	
Subgrade	Stabilization of subbase Lime-treated Cement-treated	
Base Courses	Limerock base Graded aggregate base Sand-Clay base Shell stabilized base Soil-cement base Asphalt base	composition of mixes preparation of subgrade spreading the mix compacting and finishing correcting defects & thickness priming, curing or maintaining
Surface treatment	Prime coat Tack coat	preparation of surface distribution of material spreading cover material rolling and curing
Cement-concrete	Pavement Sidewalk	subgrade preparation setting forms placing reinforcemnt placing concrete consolidating and finishing straightedging & surface correction joints and curing
Fencing	Guardrail Fencing	setting timber & steel posts placing rail or fabric reflector elements
Highway lighting		excavation and backfilling trenches for cable concrete base for light poles erecting light poles installation of luminaires

Summary of Survey Questionnaire

A survey questionnaire including the preliminary list of maintenance and construction tasks as identified above was sent to all the state highway agencies. A copy of the questionnaire survey containing these lists and other questions is provided in Appendix A. In the questionnaire, respondents were asked to identify the maintenance and construction tasks performed in their states during nighttime. They were also asked to indicate the frequency of these nighttime tasks. The results of the questionnaire survey are summarized in Table 3.3. A similar survey of all district offices of FDOT resulted in a number of projects performed at night. A summary of the survey results is provided in Table 3.4.

Out of 52, a total of 33 states responded, of which 28 respondents indicated some nighttime construction and maintenance work in their states. Some state highway agencies including California, Connecticut, Florida, Illinois, Maryland, Michigan, Missouri, New York, North Carolina, Virginia, and Washington indicated a considerable amount of nighttime highway work in their states–usually 10 percent or higher of all the awarded projects–while other states such as Arkansas, Mississippi, New Mexico, North Dakota and South Dakota reported having no experience with nighttime highway rehabilitation work.

In addition to quantity of night work, Table 3.3 also addresses the issues of application of screens or barriers between the travel lane and workzone to avoid glare to motorists and availability of lighting standards or specifications to determine workzone lighting.

Table 3.3 Summary of Questionnaire Survey of State Highway Agencies

Name of the State	Number of Nighttime projects performed in a year		Use of Screen or Barrier	Lighting Standards
	Maintenance	Construction		
Arkansas	0	?	N/A	N/A
California	10%	175	Yes	Yes
Colorado	5	?	No	No
Connecticut	20	10	No	Yes
Dist. of Columbia	0	5	No	No
Florida	20	36	No	No
Georgia	20	2	Yes	No
Hawaii	0	2	No	No
Idaho	2	0	No	No
Illinois	20	100	No	No
Iowa	25	10	Yes	No
Kansas	10	5	Yes	No
Kentucky	1%	25	Yes	No
Maine	4	?	Yes	No
Maryland	?	20	Yes	Yes
Michigan	?	7	No	Yes
Mississippi	0	0	N/A	N/A
Missouri	80	180	Yes	No
Nevada	15	1%	Yes	No
New Jersey	28	0	No	Yes
New Mexico	0	0	No	No
New York	10	10	Yes	No
North Carolina	?	20	No	Yes
North Dakota	0	0	N/A	N/A
Oklahoma	0	2	Yes	No
Pennsylvania	1-10%	1-10%	No	No
Rhode Island	2	2	Yes	No
South Dakota	0	0	N/A	N/A
Tennessee	?	1	No	No
Texas	?	?	No	No
Utah	20	1	Yes	No
Virginia	50	50	No	No
Washington	600	50	No	No
Wyoming	0	3	No	No

'?' indicates that the number of projects is undeterminable

Table 3.4 Summary of Questionnaire Survey of FDOT District Offices

District No.	District Office	Number of Nighttime Projects performed in a year	
		Maintenance	Construction
1	Bartow	5	22
2	Lake City	?	15
3	Chipley	25	?
4	Ft. Lauderdale	13	30
5	Deland	?	13
6	Miami	?	?
7	Tampa	36	10
Turnpike	Plantation	2	?

'?' indicates that the number of projects is undeterminable

Compilation & Analysis of Responses

The results of responses obtained from the nation-wide survey regarding construction and maintenance tasks during nighttime are summarized in Tables 3.5 and 3.6, respectively. Tables 3.5 and 3.6 give the relative frequency of night work as reported by various state highway agencies. To obtain most commonly performed maintenance and construction tasks, both the lists are sorted and arranged in a decreasing order of the state frequencies. Similar lists are prepared for FDOT nighttime highway construction and maintenance tasks based on the information obtained from all the seven district offices. The lists are provided as Tables 3.7 and 3.8 for construction and maintenance tasks, respectively. These lists are also arranged in the decreasing order of their frequencies.

According to Table 3.5 resurfacing, barrier wall placement, milling and pavement marking appear to be the most common construction tasks performed at night. On the other

Table 3.5 Number of States Performing Various Nighttime Highway Construction Tasks

Task No.	Construction Tasks performed at night	Frequency of Tasks		
		Frequently	Occasionally	Rarely
1.	Resurfacing	7	8	12
2.	Barrier Walls, Traffic Separators	7	8	3
3.	Milling and Removal	6	11	9
4.	Painting Stripes, Pavement Markers, Metal Buttons	4	8	4
5.	Bridge Decks construction	3	16	7
6.	Concrete Pavement construction	3	9	12
7.	Base Courses - clay, cement, asphalt	3	6	8
8.	Excavation - regular, lateral ditch, channel	3	5	10
9.	Embankment, Filling and Compaction	2	6	10
10.	Highway Signing for construction	2	6	8
11.	Subgrade stabilization & construction	2	5	10
12.	Surface treatment	2	1	5
13.	Drainage Structures, culverts & sewers construction	1	5	13
14.	Waterproofing/ Sealing	1	4	6
15.	Construction of other Concrete Structures	0	6	13
16.	Guardrail, Fencing	0	4	5
17.	Highway Lighting System construction	0	3	7
18.	Traffic Signals construction	0	1	9
19.	Landscaping, Grassing, Sodding	0	0	9
20.	Riprap placement	0	0	6
21.	Sidewalks construction	0	0	4
	Total number of responses	28		

Note : Tasks are arranged in the decreasing order of their frequencies.

Table 3.6 Number of States Performing Various Nighttime Highway Maintenance Tasks

Task No.	Maintenance Tasks performed at night	Frequency of Tasks		
		Frequently	Occasionally	Rarely
1.	Milling and Removal	5	3	0
2.	Resurfacing	5	3	0
3.	Painting Stripes/ Pavement Markers	4	3	1
4.	Sweeping and Cleanup	3	1	2
5.	Barrier Wall or Traffic Separator	3	1	1
6.	Crack filling	2	0	3
7.	Repair of Concrete Pavement	2	0	2
8.	Bridge Decks rehabilitation & maintenance	1	5	0
9.	Reworking Shoulders	1	3	2
10.	Drainage Structures maintenance & rehabilitation	1	3	0
11.	Pot filling	1	1	4
12.	Highway Signing for maintenance works	1	1	3
13.	Traffic Signals maintenance	1	1	1
14.	Landscaping/ Grassing/ Sodding	1	1	0
15.	Resetting Guardrail/ fencing	1	1	0
16.	Highway Lighting System - repair & maintenance	0	2	3
17.	Waterproofing/ Sealing	0	2	3
18.	Maintenance of earthwork/ embankment	0	2	2
19.	Riprap maintenance	0	1	0
20.	Surface treatment	0	0	3
21.	Sidewalks repair & maintenance	0	0	1
	Total number of responses		9	

Note: Tasks are arranged in the decreasing order of their frequencies.

Table 3.7 Performing Frequency of Various Construction Tasks on FDOT Nighttime Projects

Task No.	Construction Tasks performed at night	Frequency of Tasks		
		Frequently	Occasionally	Rarely
1.	Construction of other Concrete Structures	5	2	1
2.	Painting Stripes, Pavement Markers, Metal Buttons	4	5	0
3.	Resurfacing	2	1	3
4.	Milling and Removal	2	1	2
5.	Subgrade stabilization & construction	2	1	1
6.	Bridge Decks construction	1	7	1
7.	Base Courses - clay, cement, asphalt	1	2	1
8.	Barrier Walls, Traffic Separators	1	1	3
9.	Guardrail, Fencing	1	1	3
10.	Waterproofing/ Sealing	1	1	2
11.	Highway Lighting System construction	0	5	2
12.	Concrete Pavement construction	0	5	1
13.	Highway Signing for construction	0	4	3
14.	Drainage Structures, culverts & sewers construction	0	2	3
15.	Excavation - regular, lateral ditch, channel	0	1	3
16.	Traffic Signals construction	0	1	2
17.	Riprap placement	0	1	1
18.	Surface treatment	0	1	1
19.	Landscaping, Grassing, Sodding	0	1	1
20.	Embankment, Filling and Compaction	0	1	0
21.	Sidewalks construction	0	0	2
	Total number of responses	10		

Note: Tasks are arranged in the decreasing order of their frequencies.

Table 3.8 Performing Frequency of Various Maintenance Tasks on FDOT Nighttime Projects

Task No.	Maintenance Tasks performed at night	Frequency of Tasks		
		Frequently	Occasionally	Rarely
1.	Sweeping and Cleanup	7	8	3
2.	Repair of Concrete Pavement	6	2	12
3.	Bridge Decks rehabilitation & maintenance	4	4	8
4.	Resurfacing	3	7	9
5.	Milling and Removal	2	8	7
6.	Highway Lighting System - repair & maintenance	2	8	4
7.	Traffic Signals maintenance	2	7	7
8.	Painting Stripes/ Pavement Markers	2	5	7
9.	Surface treatment	2	1	2
10.	Barrier Wall or Traffic Separator	1	4	8
11.	Crack filling	1	3	6
12.	Pot filling	1	3	5
13.	Resetting Guardrail/ fencing	1	3	3
14.	Waterproofing/ Sealing	1	2	3
15.	Highway Signing for maintenance works	0	3	11
16.	Drainage Structures maintenance & rehabilitation	0	3	3
17.	Sidewalks repair & maintenance	0	2	3
18.	Reworking Shoulders	0	1	6
19.	Riprap maintenance	0	1	5
20.	Landscaping/ Grassing/ Sodding	0	1	3
21.	Maintenance of earthwork/ embankment	0	0	7
	Total number of responses		27	

Note : Tasks are arranged in the decreasing order of their frequencies.

hand, traffic signalling, lighting systems, landscaping, rip rap and sidewalks are the least preferred tasks for nighttime construction. Table 3.6 shows cleanup, concrete pavement repair and bridge deck rehabilitation as frequent maintenance activities during nighttime. In the survey, many respondents indicated that a significant amount of nighttime maintenance is attributed to emergency work in addition to regular required maintenance. Earthwork, landscaping and rip rap are the less common maintenance work conducted at night.

Factors Influencing Illumination Requirements

From literature review and discussion with experts on lighting and illumination, a number of factors affecting illumination requirements were identified. During the process of identification only those factors which are related with outdoors and nighttime highway type situations were selected. They are categorized in four categories, which include: 1) human factors, 2) environmental factors, 3) task-related factors, and 4) lighting factors. Further classification was done for the task-related factors due to their varying characteristics. Figure 3.1 shows a summary of all the factors and categories. These categories are explained in greater detail in following sections.

Human and Cognitive Factors

Visibility detection and recognition are greatly affected by various human physical, physiological and psychological factors. The important human factors affecting vision and perception are: 1) age, 2) visual acuity, 3) response characteristics, attention, and expectation, and 4) experience and familiarity.

Many studies have indicated that there is a correlation between age and visibility.

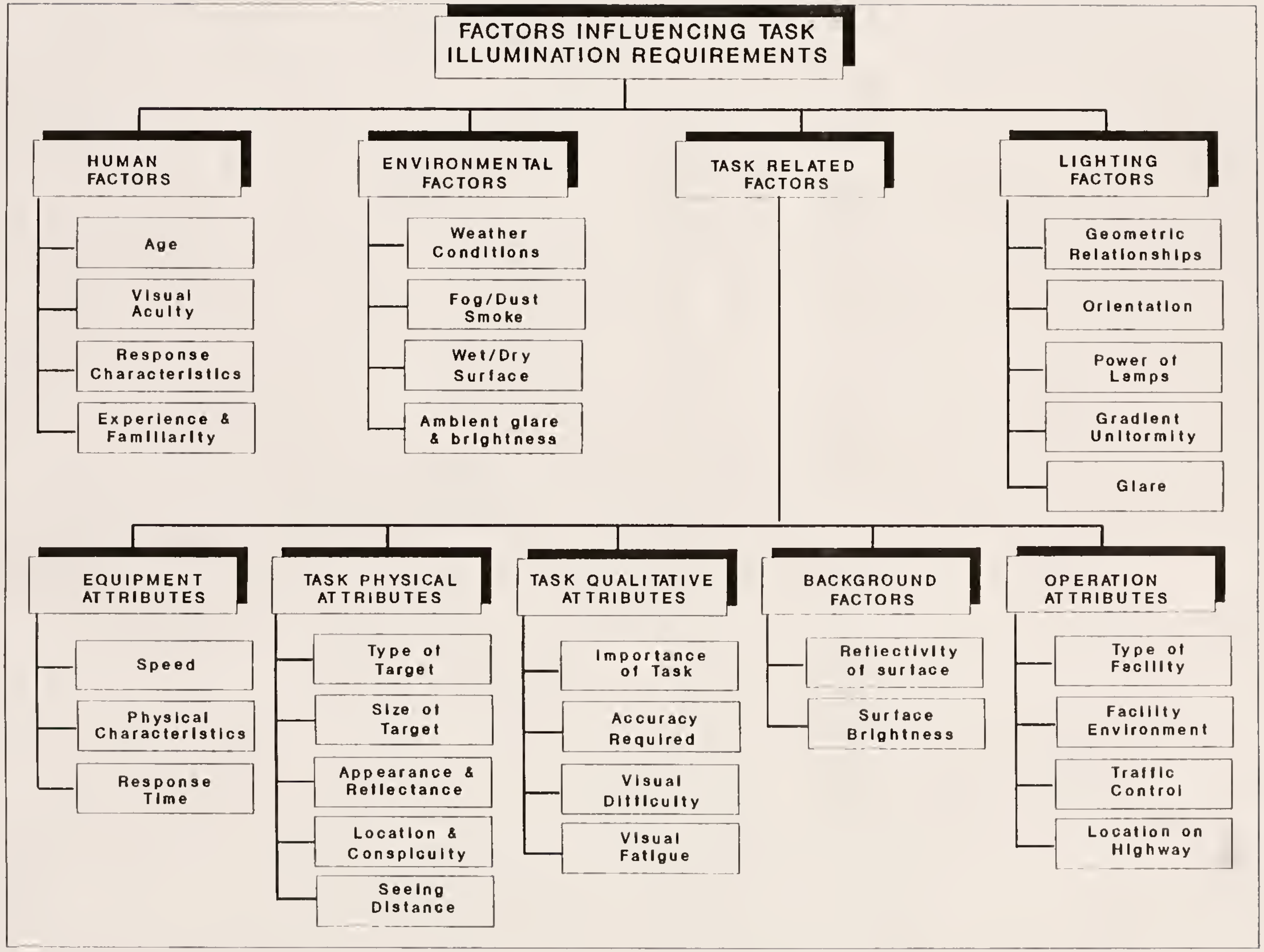


Figure 3.1 Summary of Factors Influencing Task Illumination Requirements

Ability to detect targets tends to decrease for the observers belonging to a higher age group. Similarly, visual acuity which is influenced by several human visual functions such as glare sensitivity and transient adaptation, affects an individual's perception and recognition.

On the other hand, response characteristics and cognitive behavior of an individual, experience and familiarity with a particular object also affect the process of recognizing and perceiving that object. For example, an experienced operator can identify defects on a newly paved road surface even under reduced illumination levels as compared to one having less experience with the work environment.

Environmental Factors

In this category, factors such as weather conditions, fog, surface condition and ambient brightness are included. As has been reviewed in the literature, ambient brightness helps reduce the relative contrast of the object and the background which is crucial in detecting an object. However, for night work conditions, ambient brightness helps increase the illumination level of the task and requires less additional light for adequate illumination.

Atmospheric losses may have a significant effect upon the illuminance at the observer's eye unless the viewing distance is short. In fog, the law of diminishing returns takes effect at relatively short distances. Since for nearly all the highway construction and maintenance work, distances are relatively short and visual field is more or less limited to the workzone, weather conditions and atmospheric losses may not contribute significantly to the losses in object visibility.

Task-Related Factors

Task-related factors, owing to their characteristics and variations, are further sub-categorized in the following five categories.

Equipment attributes. Utilization of various construction equipment adds another dimension to nighttime highway work compared to other external night work situations. Factors related to construction equipment influencing task illumination requirements include: 1) speed, 2) physical characteristics, and 3) response time. Speed of equipment governs the exposure time or the duration of seeing. To some extent higher speed of a particular piece of equipment can be compensated by increased illumination for adequate visibility. Physical characteristics of some equipment may restrict the vision of the operator and some of the targets may not be detectable irrespective of the quantity of illumination. For example in roller, operator's vision is restricted by the presence of drums in the visual field. Similarly for loader, paver and other equipment also, detection of targets near the equipment is determined by its position. However, for far targets quantity of illumination increases the detection distance. Required detection distance also depends on the response characteristics of the equipment. Equipment with low response time, low maneuverability or high speeds require greater detection distance and hence increased illumination.

Physical attributes of the task. Physical characteristics of the task or the target have significant effect on the quantity and quality of illumination required for its detection. Size, type, appearance, and reflectance targets and their relationship with luminance values for their identification have been discussed in detail in existing literature. Lower luminance levels are required for increase in target size. Similarly, location and level of conspicuousness of the

target also helps its identification. For the same illumination level, detection of any target in the middle of the workzone is faster than the ones on the sides. Minimum distance of seeing of a target from the observer also affects its identification. A defect on road surface is more likely to be detected by a ground crew than an operator on the equipment for same illumination level.

Task qualitative attributes. The qualitative factors associated with nighttime highway construction tasks include: 1) importance of the task, 2) accuracy desired 3) visual difficulty in performing the task, and 4) visual fatigue as a result of performance. As has been reviewed in the literature, performance increases with the level of illumination until an optimum level. Beyond this point, further increases do not necessarily deteriorate performance. From the conclusion of previous studies it can be inferred that visually difficult and visually fatiguing tasks may be performed better with an increase in the illumination level. Similarly, for the tasks requiring higher accuracy and additional attention, increased illumination is desired.

Background factors. Background factors include the characteristics of the surface on which a task needs to be performed or a target needs to be detected. Surface brightness, which also depends on background illumination, reduces the positive relative contrast for the task. Particularly when the degrees of reflectivity of the background surface and the task are in the same range, detection and recognition becomes difficult.

Operation attributes. These factors are essentially associated with the type of highway construction operation and the location where it is performed. These factors include: 1) type of facility, 2) facility environment, 3) traffic control, and 4) location on the highway. These factors influence task illumination requirements for the same task in varying capacity.

Type of facility concerns classification of the highway such as–limited access high-

ways, other arterials, collectors or local roads. Any construction or maintenance operation on limited access highways requires increased attention in forms of quality, safety and traffic control. Glare problem due to excessive illumination is more severe on these highways as speeds of vehicles are higher and drivers do not expect any interference. Facility environment includes the geographical area of the operation such as urban, semi-urban, or rural. For urban areas, street lights and roadway lighting may provide sufficient illumination to perform common highway construction tasks. The problem of glare is also limited in the urban areas because of considerable ambient brightness. However, for rural areas adaptation and glare is a serious problem because of the sudden shift from darkness to a brightly lit environment and then back to darkness, for a motorist passing through the workzone.

Illumination requirements for highway operations is also affected by the traffic control plan designed for the operation. Complete road closure or detour for a bridge or highway construction may eliminate the problem of glare to the motorists. Similarly, traffic control plans may depend on the duration of the project. For example, a short-term project may need different types of lights and illumination levels than a long-term project. Location of the work area on the highway or bridge, such as – on the right-of-way, median, shoulder, ramp, or intersection, also affects the illumination specification and requirements. Since reflectivity of the background surface depends on the location on the highway, illuminance values to facilitate detection of a target may vary with the location of task. For example, as shown in Figure 2.1 the retro-reflectivity of grass, gravel shoulder, asphalt pavement, and concrete pavement and deck is different and varies with the distance from the lamp. As a result, illuminance values for the same surface luminance will be different.

Lighting Factors

Factors associated with lighting provisions which can influence task illumination requirements include: 1) geometric relationship, 2) orientation, 3) power and type of lamps, 4) gradient uniformity, and 4) glare. Geometric relationships between light plant, observer and location of the object sometimes effect the amount of illumination required as the reflectance of background surfaces varies with difference in positions and hence the luminance. Similarly, orientation, power and types of lamps also affect reflectance and contrast. Uniformity is associated with the quality of illumination which is important for seeing detail in the work area. Uniformity, depending on the task characteristics, also affects the quantity of illumination required to perform the task. Glare of both types, discomfort and disability, is a direct result of the quantity of illumination. Glare is not only affected by the power and type of lamps but also by the size of light source, orientation and reflectance of the background surface.

Identification of Significant Factors

Although all the factors discussed above influence task illumination requirements, the degree of influence varies. A list of factors which significantly affect the illuminance levels for highway construction tasks is given in Table 3.9. The factors in the table have been selected from the factors described above and as a result of literature review for specifically for highway construction related visual tasks. Various levels are assigned to the factors for measurement. A number of these levels are subjective in nature as its not feasible to introduce objective levels for all the factors, particularly keeping construction activities in view. There

has been no priority or significance level associated with these factors.

Table 3.9 List of Factors Significantly Affecting Nighttime Highway Task Visibility

Name of the Factor	Suggested Levels of the Factors			
Size of the objects to be seen	Very Fine	Small	Medium	Large
Shape of the objects to be seen	Flat	1-dimensional	3-dimensional	
Contrast of object & background	< 30%	30-70%	> 70%	
Age of Workers	under 40	40-55	over 55	
Reflectance of the surface	< 0.3	0.3 - 0.7	> 0.7	
Time spent in seeing	few seconds	1 - 5 min	half hr +	
Importance of Task	low	medium	high	
Importance of Speed	low	medium	high	
Importance of Accuracy	low	medium	high	
Visual Difficulty in seeing	low	medium	high	
Visual fatigue experienced	low	medium	high	
Seeing distance of the object	1 - 5 ft	5 - 15 ft	> 15 ft	
Safety & Glare considerations	Non-critical	Moderately Important	Critical	
Importance of Uniformity	Non-critical	Moderately Important	Critical	

As stated earlier all the factors in the table are not assigned a significance level or degree of influence. These factors, however significant, do not affect illumination

requirements identically and vary in their degree of influence. Some factors are envisaged to have direct and consistent effect on the lighting levels required for seeing. These conclusions are drawn from the findings from literature review and experienced personnel. As a result another short listed summary of factors is prepared to further evaluate their effect and are eventually included in the data analysis and model development. The factors which are included in the model for their significance are as follows

1) speed associated with the task
2) accuracy or importance desired for the task
3) reflectance of the background surface
4) seeing distance of the object from the observer
5) relative size of object to be seen.

None of the human factors are included in the list because of the presumption that every crew or operator is a normal attentive observer in a given age group. Moreover, during field investigation, it was determined that on FDOT projects, in general, equipment operators belong to one age group. Visual and other variations among crew members for highway construction work do exist. However, lighting guidelines should be based upon normal visual capacity with sufficient allowance for individual variation. Similarly, environmental factors are also found to have an insignificant effect compared to the five selected factors, which are all task related factors and are representative of their sub-categories.

Determination of Factor Levels

For comparison purposes, it was considered necessary to quantify these selected factors. Since determining and assigning number values to the factors was found difficult in

actual field conditions, certain subjective levels were assigned to these factors from practical considerations. Table 3.10 provides the factors and their subjective levels.

Non-Highway Task Matrix

Description

Although subject of lighting has not been studied in detail for tasks related to construction industry, for other industrial applications there has been extensive work existing in the area of lighting. A need was felt to take advantage of the already existing guidelines and standards. As a result an approach is adopted to develop some sort of comparison criteria and relate construction tasks to visually similar other industry tasks. Other industries excluding highway construction industry are addressed as Non-highway Industries. Since the non-highway tasks are distinctly different from highway tasks, developing a suitable and reliable criteria was crucial to comparative analysis. A set of factors identified in the previous section were utilized to perform the comparison. Care was taken to choose mostly outdoor non-highway tasks as highway construction is an outdoor activity.

Sources of Information

The visual requirements in a typical highway construction task are similar to the visual requirements of certain outdoor industrial tasks. For comparison with highway tasks purposes, a list of equivalent non-highway tasks was identified and their illuminance levels were obtained from ANSI/IES recommendations for outdoor industrial spaces (8). The typical industrial areas selected for the matrix include: 1) Automotive Industry, 2) Iron & Steel

Table 3.10 Factors Influencing Task Illumination Requirements and Their Subjective Levels

Task No.	Factors	Subjective Levels
1	Importance and accuracy of the task	L - Low M - Medium H - High
2	Background Reflection	L - Low M - Medium H - High
3	Speed	N - Not applicable L - Low M - Medium H - High
4	Size of the object to be seen	F - Fine S - Small M - Medium L - Large
5	Distance of Seeing	S - 1 to 5 ft M - 5 to 15 ft L - >15 ft

Industry, 3) Petrochemical Industry, 4) Pulp & Paper Industry, 5) Industrial Outdoor Spaces etc.

Development of Matrix and SAS Dataset

Based on the characteristics of the tasks identified for non-highway activities, they were assigned different levels of various factors as determined in the earlier section. Table 3.11 provides the matrix of selected non-highway outdoor tasks, their area, factor descriptions, and recommended illuminance levels. A SAS dataset has been developed from the matrix provided in Table 3.11. The factors are assigned identification for SAS dataset, which are: 1) F1 for Importance of factors, 2) F2 for Background reflection, 3) F3 for Speed, 4) F4 for Relative size, 5) F5 for Distance for seeing, and 6) LEVEL for suggested illuminance levels. The dataset also includes fields for area and activity for non-highway tasks.

Summary

In this chapter various model components were determined and formulated. Typical highway nightwork activities were identified from various department of transportation documents. This preliminary list was sent to all the state highway agencies and their responses were summarized. Results of the survey were incorporated and list of highway activities were modified. Tasks involving similar activities were classified in the categories for simplication of highway task list.

From the review of literature several factors influencing illumination requirements were identified. The categories developed to include all the factors having influence on

Table 3.11 Factor Description and Illuminance Levels of Outdoor Industrial Tasks and Spaces

Area	Name of the Activity	Factors					Recom.
		Imp.	Refl.	Spd.	Size	Dist.	Level (fc)
Automotive Industry	Frame Assembly	H	M	L	S	S	50
	Welding Area	H	H	N	S	S	50
	Machining Operations	H	H	H	F	S	75
	Coal Yards & Oil Storage	L	L	N	L	L	0.5
	Outdoor Substation, Parkin	L	L	N	L	L	1.5
	Entrance, Truck Maneuveri	L	L	L	L	L	5
	Furnace Area, Sheet Rollin	H	M	N	M	S	30
Iron & Steel Industry	Mold Yard	L	L	N	M	L	5
	Scrap Stock Yard	M	M	N	M	L	10
	Hot Top Storage	M	H	M	M	L	10
Petrochemical Industry	Pump rows, valves, manifol	L	L	N	M	L	5
	Heat Exchangers	L	L	N	M	L	3
	Maintenance Platforms	L	L	N	L	L	1
	Operating Platforms	L	L	N	M	L	5
	Cooling towers, equipment	L	L	N	M	L	5
	Furnaces	L	L	N	M	L	3
	Active Ladder, Stairs	L	L	L	L	L	5
	General Area	L	L	N	L	L	1
	Extruders & Mixers	M	M	L	M	M	20
	Conveyors	L	L	M	L	L	2
	Outdoor plants, equipment	L	L	N	S	M	5
	Outdoor Substation	L	L	N	L	M	2
	Plant Road: Freq. use	L	L	M	L	L	0.4
	Plant Road: Infreq. use	L	L	L	L	L	0.2
	Plant Parking Lots	L	L	L	L	L	0.1
	Outdoor bulk storage	L	L	N	L	L	0.5
	Large Bin Storage	L	L	N	L	M	5
	Small Bin Storage	M	M	N	S	M	10
	Small Parts Storage	M	M	N	F	M	20
Pulp & Paper Industry	Groundwood Mill Grinder	H	M	H	S	M	70
	Beater Room	H	M	L	M	M	30
	Roll Dryer	H	M	M	S	M	50
	Cutting & Sorting	H	M	H	S	S	70
	Active Warehouse	M	M	L	M	M	20
	Shipping Truck Shed	M	M	L	M	M	20
	Roadways	L	L	M	L	L	0.4
	Log Pile	L	L	N	M	L	3
	Log Unloading	L	L	L	M	M	5
Industrial Outdoors	Excavation	L	L	N	L	M	2
	General Construction	M	M	N	M	M	10
	Active entrance	L	L	L	L	L	5
	Inactive entrance	L	L	N	M	L	1

lighting requirements included: 1) Human & cognitive factors, 2) Environmental factors, 3) Lighting factors, and 4) Task related factors. From the list of factors, some factors were short listed which had significant effect on the illumination. Factor levels were also determined subjectively to include in the model and to facilitate analysis. A list of non-highway tasks were selected from literature and their suggested levels were utilized to prepare a SAS dataset. This dataset is used for analysis in the next chapter.

CHAPTER 4
MODEL DEVELOPMENT

Introduction

It has already been hypothesized and also proven by a number of studies that the selected factors such as accuracy and importance, reflectivity, speed, size, and seeing distance have varying influences on the requirement of an illumination level for a particular task. In order to determine a functional relationship between illumination level and various factors, a model approach is adopted. Although the significant affects of these factors are also documented by some studies, their exact contributions are not known particularly in a highway workzone type of situation. Moreover, prediction of a definite lighting level for the given conditions of a construction task is difficult in the absence of a quantitative approach.

In this chapter a mathematical model approach has been suggested for determining the illumination level for any given highway construction task. Figure 4.1 shows the flow chart of model development procedure adopted in this chapter. The components formulated in the previous chapter have been utilized to develop a problem of one dependent variable and five independent variables. A statistical general linear model is proposed and discussed. To simplify computing procedures, assistance of the SAS system has been solicited. Various relevant SAS procedures along with their applicability have also been described.

The SAS dataset, developed earlier, has been modified to develop the database with

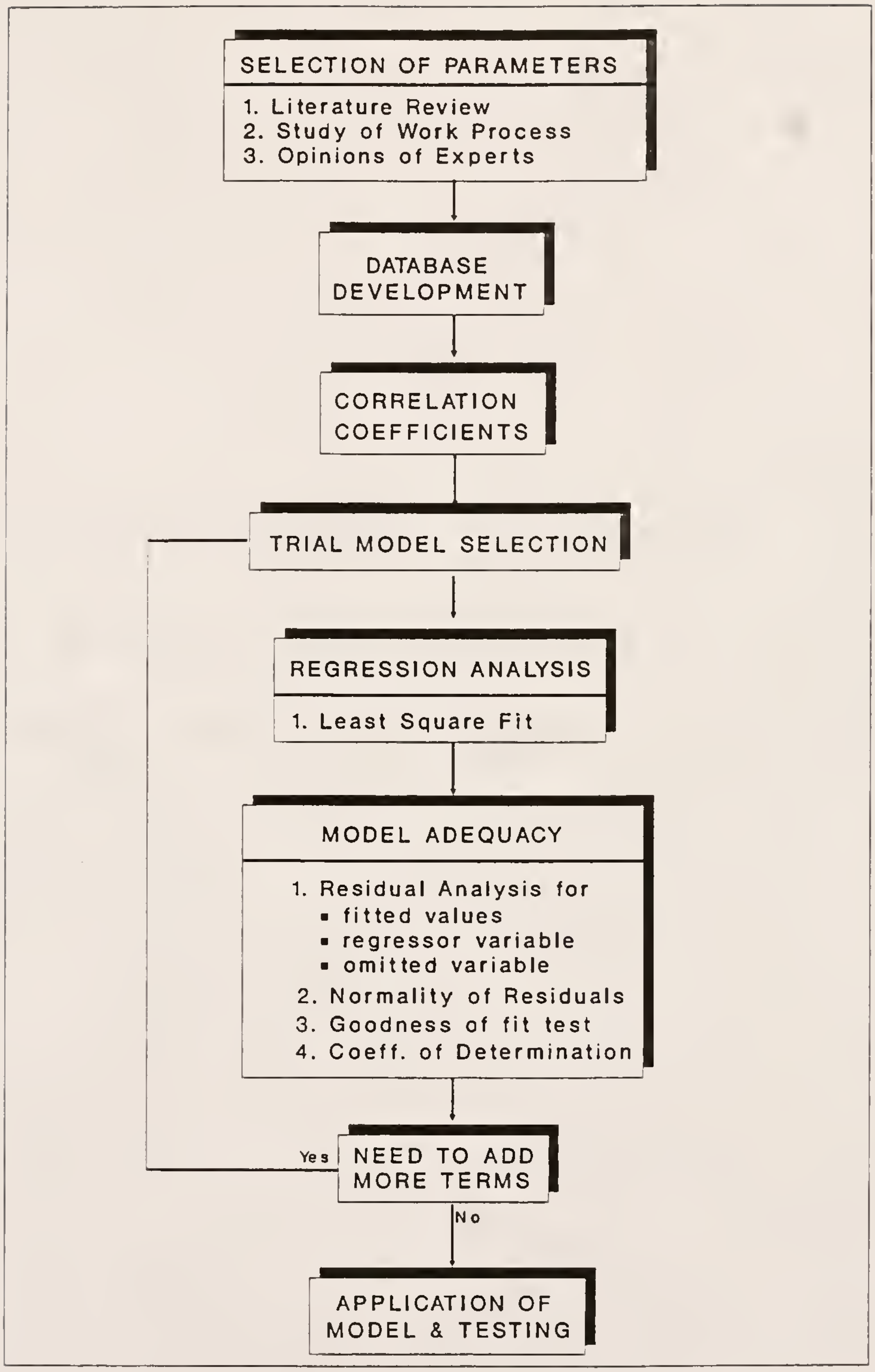


Figure 4.1 Flow Chart of Model Development Procedure

numerical values for non-highway industrial outdoor applications and their illumination recommendations. Data is analyzed to determine the correlation between various factors and illumination level. Several trial models have been selected and analyzed using SAS system. Regression analysis, which is frequently used to analyze data from unplanned experiments, is performed on all the models and the corresponding hypothesis has been tested. Models are evaluated for lack of fit and adequacy. With the help of residual plots, regression coefficients and error sum of squares, the best suited model is selected.

Model Approach

Modeling is defined as a process for determining, defining and explaining the relationships among a set of variables. Models usually involve two groups of variables. They are

1. Dependent variable, sometimes also referred to as response variable, is defined as the variable to be predicted from a given set of variables.
2. Independent variables, also sometimes referred to as predictor variables, are the other variables that are to be evaluated in a research.

In order to predict the value of dependent variable, levels or settings of the independent variables need to be taken into account. The estimation problem can be greatly simplified if models relating a response (dependent variable) to a set of independent variables are considered. To demonstrate these models, in this section, various linear and multiple regression models are discussed. In the first part of this section a model is formulated and estimation and test procedures are developed when the dependent variable is related to one independent variable, which is later on expanded to include models and inferences when the dependent variable is related to more than one independent variable.

Regression Models

Suppose a single dependent variable or response y depends on independent or regressor variable x. The relationship between these variables is characterized by a mathematical model called a regression equation. The regression model is fit to sample data. In some instances, the experimenter knows the exact form of the true functional relationship between y and x. However, inmost cases, the true functional relationship is unknown, and the experimenter chooses an appropriate function to approximate.

Statistical consideration concerning regression includes various methods. The flow chart presented in Figure 4.2 shows various regression methods. Regression methods are frequently used to analyze data from unplanned experiments, such as might arise from observation of uncontrolled phenomena, or historical records. Regression analysis is also highly useful in designed experiments. Generally, the analysis of variance in a designed experiment helps to identify which factors are important, and regression is used to build a quantitative model relating the important factors to the response.

Simple linear regression

To determine the relationship between a single regressor variable x and a response variable y, where x is usually assumed to be a continuous

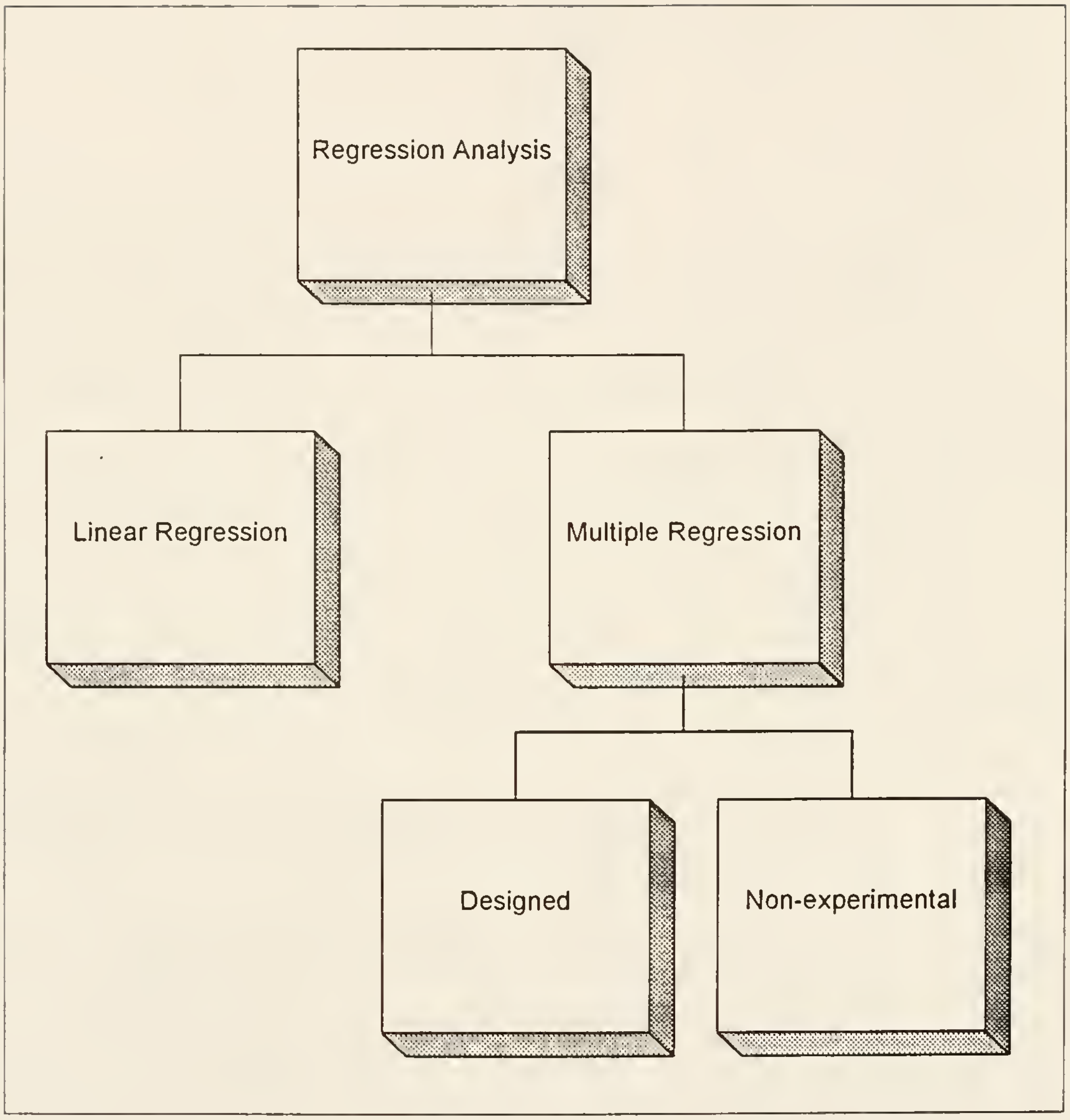


Figure 4.2 Various Regression Methods Source: Ref. 54

variable controllable by the experimenter, a simple linear model can be suggested. If the true relationship between y and x is supposed to be a straight line, the model can be described as (54)

$$y = \beta_o + \beta_1 x + \epsilon$$

where, β_o and β_1 are unknown constants and ϵ is a random error with mean zero and variance σ^2.

The expected value of y for each value of x is given by

$$E(y) = \beta_o + \beta_1 x$$

To formulate an estimate for E(y), given sample information is used to construct estimates, $\hat{\beta}_o$ and β_1, of the parameters β_o and β_1. The method of least squares is used for estimating the line and its constants. The method chooses the prediction line that minimizes the sum of the squared errors of prediction for all sample points. The least square estimates are given as

$$\hat{\beta}_1 = \frac{Sxy}{Sxx}$$

and $\hat{\beta}_o = \bar{y} - \hat{\beta}_1 \bar{x}$

where

$$Sxx = \Sigma (x - \bar{x})^2 = \Sigma x^2 - \frac{(\Sigma x)^2}{n}$$

$$Sxy = \Sigma (x - \bar{x})(y - \bar{y}) = \Sigma xy - \frac{(\Sigma x)(\Sigma y)}{n}$$

Least square method

To describe the least square method, a graphical representation is provided in Figure 4.3. As shown in the figure, the quantity $(y - \hat{y})$ represents that the portion of the distance between y and $\bar{y}$ that can not be accounted for by the independent variable x and is attributed as error. Therefore, the sum of squared prediction error from the titled model $\hat{y} = \hat{\beta}_o + \hat{\beta}_1 x$ is $\Sigma(y - \hat{y})^2$.

From the analysis of the model, all the errors can be formulated as

sum of squares about the mean	=	sum of squares due to regression	+	sum of squares for error

Another way to view this equation and explain the variability in the y-values is (55)

$\Sigma (y - \bar{y})^2$		$\Sigma (\hat{y} - \bar{y})^2$		$\Sigma (\bar{y} - \hat{y})^2$
total variability in y-values	=	variability explained by model	+	unexplained variability

To predict y based on the independent variable x, the larger the explained variability is relative to the unexplained variability, the better the model fits the data, and should lead to a more precise prediction of y based on x.

Correlation

One measure of the strength of the relationship between two variables x and y is called the coefficient of linear correlation and can be computed as (55)

$$\gamma = \frac{Sxy}{\sqrt{Sxx\ Syy}} = \hat{\beta}_1 \sqrt{\frac{Sxx}{Syy}}$$

where

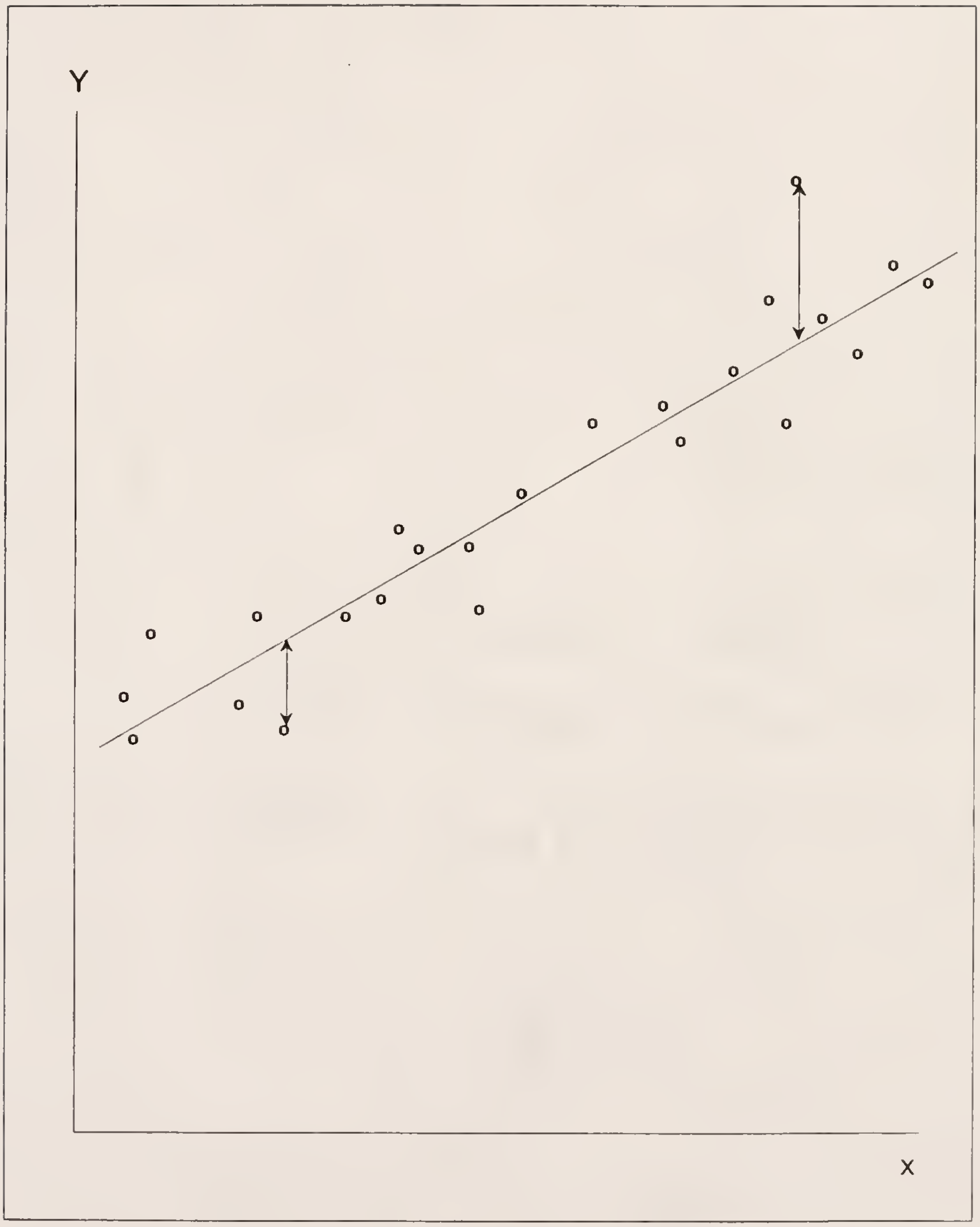


Figure 4.3 Graphical Representation of Least Sqaure Method

Source: Ref. 55

$$Syy = \Sigma (y - \bar{y})^2$$

γ lies between -1 and +1. γ greater than zero indicates a positive relationship and $\gamma < 0$ a negative linear relationship between x and y. $\gamma = 0$ indicates no linear relationship. To account for the total variability of the y-values by the independent variable x, γ^2 is utilized. Similarly, $1 - \gamma^2$ represents that proportion of the total variability of the y-values that is not accounted for by the variable x.

Multiple regression and general linear model

The simplest type of regression model relating the dependent variable y to a quantitative independent variable x has been discussed earlier. However, not all data sets are adequately described by a model, the expectation of which is a straight line. In such cases a multiple regression model relating y to a set of quantitative independent variables is used which can be represented as (55)

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots \beta_R x_R + \epsilon$$

Any of the independent variables may be powers or combination of other independent variables; for example x_2 might be x_1^2, x_3 might be equal to $x_1\ x_4$, and x_4 might be log x_1, etc. The other parameters β_1, $\beta_2 \ldots \beta_p$ in the multiple regression equation are sometimes called partial slopes and β_o is called as y-intercept.

The only restriction with the above model is that no x is a perfect linear function of other x's. The above model is also known as the General Linear Model.

Confidence intervals and prediction limits

The estimate of expected value of y, E(y) for a specific setting of x can be obtained by evaluating the prediction equation

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$$

Assuming that the ϵ is normally distributed, a 100 (1 - α)% confidence interval for E(y) is given by following formula (55)

$$C.I. = \hat{y} \pm t_{\alpha/2}\, S_\epsilon \sqrt{\frac{1}{n} + \frac{(x - \bar{x})^2}{Sxx}}$$

where

$$S_\epsilon^2 = \frac{SSE}{n - 2}$$

$$SSE = \Sigma(\bar{y} - \hat{y})^2$$

and

t-value is based on df = n - 2

For the experimenter to predict the actual value of y for a given x, a set of prediction limits can be specified. These limits are also explained in Figure 4.4. The equation for prediction limits is given by

$$PL = \hat{y} \pm t_{\alpha/2}\, S_\epsilon \sqrt{1 + \frac{1}{n} + \frac{(x - \bar{x})^2}{Sxx}}$$

Criteria for Model Evaluation

After the regression models have been developed, they are evaluated for their adequacy. Various questions that arise include: 1) Does the regression model adequately represent the data? 2) Is there a need to add more terms? and 3) How to identify the outliers?

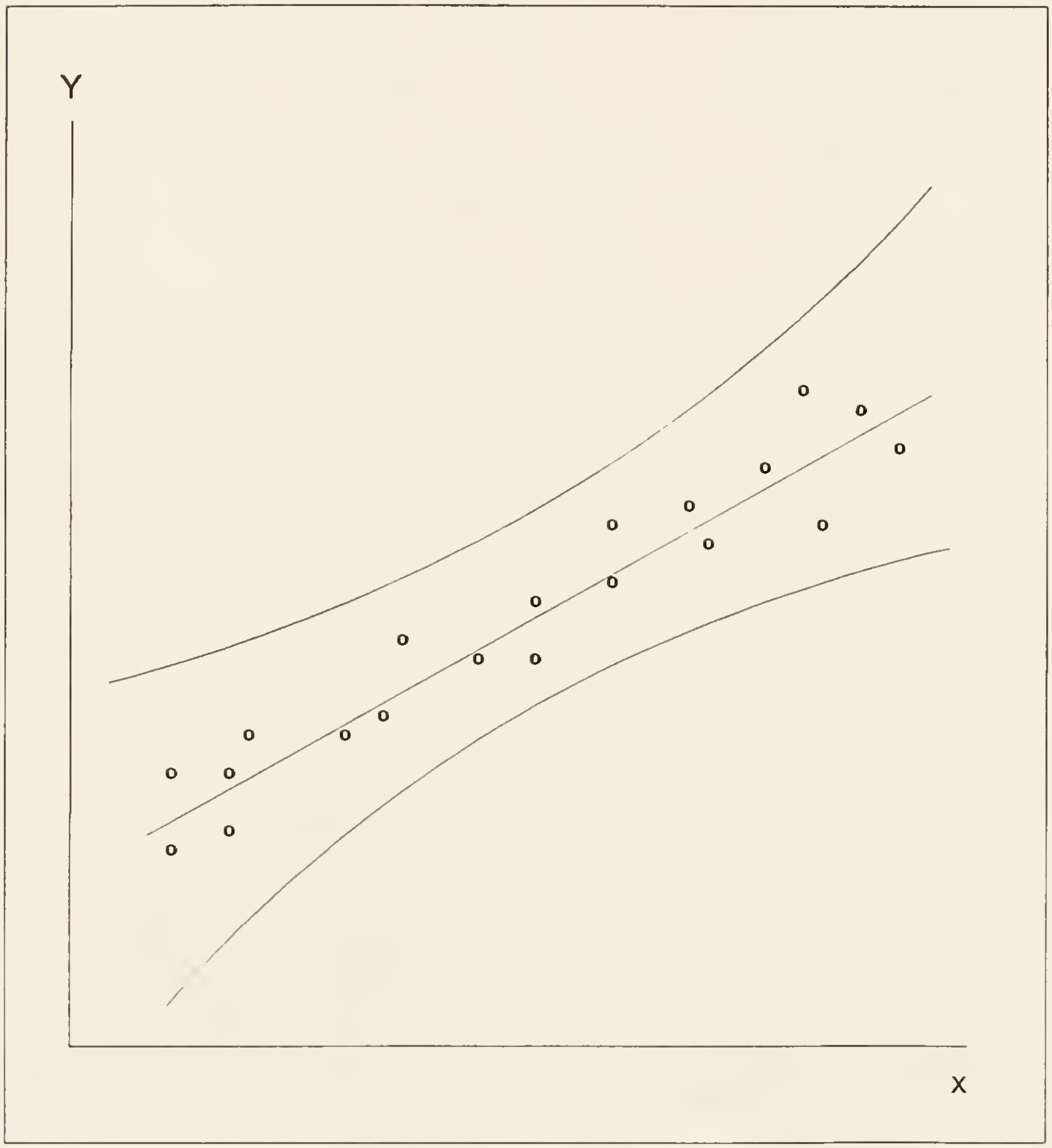


Figure 4.4 Graphical Representation of Prediction Limits

Source: Ref. 55

that is, observations that don't fit in with rest of the data. Basic regression diagnostics and fitting regression models are interwined. First the model is fit, and then it is examined using diagnostics. This may lead to fitting a second model, which is also examined by diagnostics. The process continues until a model is found that fits the data well. There are various methods commonly utilized to examine the models, which include: 1) Residual Analysis, 2) Lack of Fit Test, 3) Coefficient of Determination, 4) Mallows' C_p Statistic, and 5) Hypothesis Testing for Multiple Regression. The methods are briefly described as follows.

Residual analysis

Residuals are the differences between observed and predicted values. Residual analysis is an important part of regression diagnostics. One of the most effective methods of residual analysis is plotting residuals. It is helpful to examine a normal probability plot, a plot of residuals versus fitted values, and a plot of residuals versus each regressor variable. In addition, if there are variables not included in the model that are of potential interest, then the residuals should be plotted against these omitted factors. Figure 4.5 shows some possible patterns in residual plots (56). The nature of these plots show if the model is good or not. As shown in the figure if the model has all the terms it needs, then a plot of residuals against independent variables or against predicted values should look like a random scattering of points (a horizontal band). A curved plot which gives an up-and-down trend, starts on the left with negative values, changing to positive, and then back to negatives. This pattern indicates that a quadratic term is needed in the model. A plot of residuals against independent variables which has a definite increasing or decreasing trend indicates that the independent variable needs to be added in the model. If the plot of predicted and residual values shows a systematic increasing or decreasing trend, it implies that the variances are not equal and data

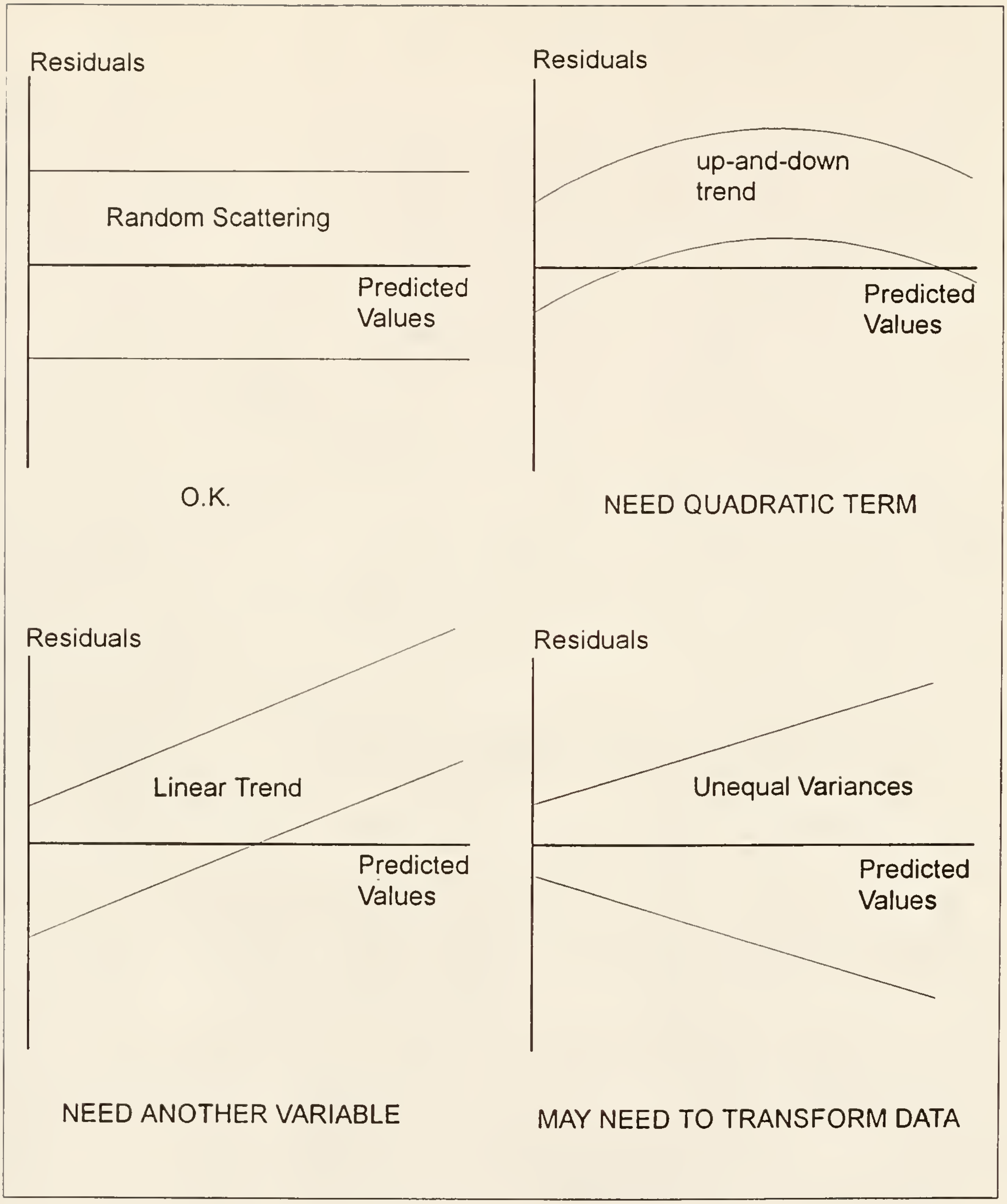


Figure 4.5 Some Possible Patterns of Residual Analysis

Source: Ref. 56

may needed to be transformed. Transformation of data is usually done by performing certain mathematical operators.

If an observation is not adequately represented by the model, then the residual for that observation is usually large because the predicted value tends to differ substantially from the observed value. If only a small percent of observations have large residuals, then these observations are defined as outliers. Outliers need to be checked carefully before rejecting as they may be there for some cause not considered in the model.

Lack-of-fit test in linear regression

Regression models are often fitted to data when the true functional relationship is unknown. In order to check the assumed order of the model as correct, a test is performed which is also known as "goodness of fit" test. The hypothesis to be tested is (54)

H_0: The model adequately fits the data

H_1: The model does not fit the data

The test involves partitioning the error or residual sum of squares into the following two components.

$$SS_E = SS_{LOF} + SS_{LOF}$$

where SS_{LOF} is the sum of squares attributable to "pure" experimental error, and SS_{LOF} is the sum of squares attributable to the lack of fit of the model. For n observations and m distinct level of X, the test statistic for lack of fit would be

$$F_0 = \frac{SS_{LOF} /(m - 2)}{SS_{PE} /(n - m)} = \frac{MS_{LOF}}{MS_{PE}}$$

and hypothesis is rejected if $F_0 > F_{\alpha,m-2,n-m}$.

This test procedure may be easily introduced into the analysis of variance conducted for the significance of regression. If the null hypothesis of model adequacy is rejected, then the model must be abandoned and attempts made to find a more appropriate model. In fitting a regression model to experimental data, a good practice is to use the lowest-degree model that adequately describes the data. The lack-of-fit test may be useful in this respect.

Coefficient of determination

Coefficient of determination is defined as a ratio and is often used to judge the adequacy of a regressor model. It is expressed as (54)

$$R^2 = \frac{SS_R}{S_{YY}}$$

where, $0<R^2\leq 1$. R^2 is loosely referred as the proportion of variability in the data explained or accounted for by the regression model. If the regressor X is a random variable , so that Y and X may be viewed as jointly distributed random variables, then R is just the simple correlation between Y and X. However, if X is not a random variable, then the concept of correlation between Y and X is undefined.

The statistic R^2 should be used with caution, since it is always possible to make R^2 unity by simply adding enough terms to the model. Also, R^2 will always increase if we add a variable to the model, but this does not necessarily mean the new model is superior to the old one. Unless the error sum of squares in the new model is reduced by the an amount equal to the original error mean square, the new model will have a larger error mean square that the old one because of the loss of one residual degree of freedom.

Mallows' C_p statistic

The problem, as stated before also, with using R^2 criterion for the best-fitting regression equation is that R^2 increases for each independent variable added to the model, even when the new X has very little predictive power. To overcome this problem another criterion known as C_p statistic is introduced by Mallows that do not increase with the addition of each X (57).

In general, if a model is chosen that leaves out one or more "important" predictor variables, the model is underspecified and the additional variability in the y-values that would be accounted for with these variables becomes part of the estimated error variance. On the other hand, if a model is chosen that contains one or more "extraneous" predictor variables, the model is overspecified and there is chance of having a multicollinearity problem. The criterion based on C_p statistic seems to balance some pros and cons of previously presented selection criteria, along with the problem of over- and underspecification, to arrive at a choice of the best-fitting subset regression equation. The C_p statistic is (55)

$$C_p = SSE_p/S\epsilon^2 \ - \ (n - 2p)$$

where SSE_p is the sum of squares for error from a model with p parameters (including B_0) and $S\epsilon^2$ is the mean square error from the regression equation with the largest number of independent variables. For a given selection problem C_p is computed for every regression equation that fits. According to Mallows the best fitting model should have C_p equal to the number of parameters p.

Hypothesis testing in multiple linear regression

In multiple linear regression the experimenter frequently tests hypotheses about the model parameters. To test the significance, following test can be utilized (54)

H_0: $b_1 = b_2 = \ldots\ldots = b_k = 0$

H_1: $bi \neq 0$ at least one i

Rejection of H_0 in the above test implies that atleast one variable in the model contributes significantly to the fit. This test is a generalization of the procedure used for lack-of-fit test in linear regression. The total sum of squares S_{yy} is partitioned into regression and error sums of squares

$$S_{yy} = SS_r + SS_e$$

Therefore, the test procedure for H_0: $bi = 0$ is to compute

$$F_0 = (SS_r /k)/ (SS_e/(n-k-1)) = MS_r/MS_e$$

and to reject H_0 if $F_0 > F_{\alpha,k,n-k-1}$.

Hypotheses tests are frequently performed on the individual regression coefficients. Such tests would be useful in determining the value of each of the regressor variables in the model. For example, the model might be more effective with the inclusion of additional variables, or deletion of one or more of the variables already in the model. Adding a variable to a regression model always causes the sum of squares for regression to increase and the errorsum of squares to decrease. Furthermore, by adding an unimportant variable to the model, the mean square error can actually increase, thereby decreasing the usefulness of the model. The hypotheses for testing the significance of any individual coefficient, for example, bi, are

H_0: $bi=0$

H_1: $bi\neq0$

$$t_0 = b_i/\sqrt{(MS_e C_{ii})}$$

and H_0:b_i=0 is rejected if $|t_0| > t_{\alpha/2,n-k-1}$.

Fundamental Assumptions

The basic assumptions for a regression model of the form

$y_i = \beta_o + \beta_1 x_{i1} + \beta_2 xi_2 + \ldots\ldots + \beta_k x_k + \epsilon_i$

are (55)

1. Zero expectation: $E(\epsilon_i) = 0$ for all i.
2. Constant variance: $V(\epsilon_i) = \sigma^2_\epsilon$ for all i.
3. Normality: ϵ_i is normally distributed.
4. Independence: The ϵ_i are independent.

Since the assumptions for multiple regression are written in terms of the random errors ϵ_i, the assumptions are checked by using the residuals, which are estimates of the ϵ_i. The first assumption, zero expectation, deals with model selection and whether or not additional independent variables need to be included in the model. Usually if the adequate independent variables are identified and appropriate form of multiple regression model is selected, assumption 1 holds.

The assumptions of constant variance can be examined using residual plots. To detect nonconstant variance a plot of residuals versus the predicted values is studied. As shown in Figure 4.5 if the plot looks similar to the fourth plot in the figure, variances are not constant and data may need to be transformed to hold the second assumption. The third assumption for multiple regression is that of normality of the ϵ_i. Skewness and/or outliers are examples of forms of nonnormality that may be detected through the use of certain scatterplots and residual plots. A plot of the residuals in the form of a histogram or a stem-and-leaf plot helps to detect skewness. By assumption, the ϵ_i are normally distributed with mean zero therefore

the histogram of the residuals should be symmetrical about zero. Another way to detect nonnormality is through the use of a normal probability plot of the residuals.

The final assumption is that the ϵ_i are statistically independent, and hence uncorrelated. When the time sequence of the observations is known, as is the case with time series data where observations are taken at successive points in time, it is possible to construct a plot of residuals versus time to observe where the residuals are serially correlated.

SAS Procedures

In this section some of the SAS procedures utilized in the data analysis for this study are mentioned and discussed. SAS is one of the most, or probably the most, versatile and powerful language currently available and performing a variety of statistical functions. In this section, analysis methods are integrated with SAS statements needed to perform the analysis and explanation of the output. Mainly two statistical procedures: 1) correlation analysis and 2) regression analysis are discussed in this study. The analyses are statistical methods used to answer questions about relations between variables. The correlation coefficient is a number that measures the strength of the relation between variables. Regression analysis uses equations to describe how one variable is related to another variable or group of variables.

It is usually informative to plot the data before computing any statistical measures. For this reason, to examine the relation between various factors and illumination level, data is plotted using PLOT procedure of SAS. An example of statements with PLOT procedure is given below.

```
PROC PLOT DATA = <data-set-name>;
PLOT   <y-variable * x-variable>;
RUN;
```

The PLOT tells the PLOT procedure what variables to plot. The variable on the vertical axis is specified first, followed by an asterisk and then the variable on the horizontal axis. The program code of PLOT procedure are provided in Appendix B.

After determining the relationship between two variables, their strength needs to be determined. A number called the correlation coefficient measures the strength of relation between two variables. Values of this coefficient range from -1.0 to +1.0, where -1.0 indicates positive correlation and -1.0 indicates negative one. A value equal to or close to 0 corresponds to a scattering of points that shows neither an upward nor a downward trend. In SAS, CORR procedure can be utilized to determine correlations between two or more variables. The general form of the statements for CORR is shown below:

```
PROC CORR DATA = <data-set-name>;
VAR   <variables>;
RUN;
```

The program used for correlation analysis of all the variables and its results are included in Appendix C. Although correlation analysis establishes relationship between two or more variables, caution must be taken while interpreting the coefficients. One such caution is related to causation. When two variables are highly correlated, it does not necessarily mean that one causes the other. Therefore, before correlation analysis, some sort of functional relationship should be established between the variables.

Although a correlation coefficient tells that some type of relation exists, it fails to indicate several other quantitative inferences such as future predictions, confidence limits and other estimates. To investigate the form of the relation between the variables, regression

analysis is used. One way to use regression is to fit a straight line through a set of points. However, for scattered data points or for data sets without an obvious pattern in the plot, different people can draw very different lines through the data and get widely differing predicted values. Using regression analysis, every time only one exact same straight line is obtained and the process is called fitting a regression line. The method used most often for fitting a line uses a principle called least squares. In SAS, REG procedure is most commonly used for regression analysis. A MODEL statement is also required to fit a line to data. The ID statement identifies observations on some part of the output. Regression with more than one independent variable is referred to as multiple regression. To use PROC REG for multiple regression, multiple MODEL statements are used to examine different models. The general form of the procedure is shown below:

```
PROC REG DATA = <data-set-name>;
MODEL   <dependent-variable = independent-variables>;
ID  <id-variable>;
VAR   <variables>;
RUN;
MODEL    <different model than the first one>;
RUN;
```

There are various options available with REG procedure. Some of important ones are--CLI to print predicted values and prediction limits, CLM to print predicted values and confidence limits for the mean, U95 and L95 contain upper and lower prediction limits, and U95M and L95M contain upper and lower confidence limits for the mean.

The output REG procedure provides analysis of variance, various parameter estimates and model information. In parameter estimate it determines degrees of freedom, standard error, t-values for testing null hypothesis, and p-value for the t-value. In analysis of variance

REG procedure provides information on sources of variations and their degrees of freedom, sum of squares, mean square, F-value, and R^2. Various different models were selected for analysis in this study, which are included along with their results in Appendix C and have been discussed in detail in subsequent sections.

Database Development

To develop database for analysis and model design, the SAS dataset created in earlier was utilized. The SAS dataset was developed for mainly industrial outdoor activities and application areas having similar visual requirements as typical nighttime highway construction tasks. The dataset had several fields including: 1) ID for identification code, 2) AREA for application area, 3) ACTIVITY for outdoor activity in industrial applications, 4) F1 to F5 for identification for all the five factors, and 5) LEVEL for the recommended illuminance level. Since in the dataset levels for various factors from F1 to F5 were subjective, they needed to be converted to numeric values for data analysis. A different SAS program code was written to assign numerical values to these subjective factor levels. The assigned values are summarized in Table 4.1.

Thus the new SAS dataset after such conversion was obtained which in addition to the above-mentioned fields, had five more fields denoted by F11 to F55. The numerical values of these fields along with the LEVEL were used for various data analysis including determination of correlation coefficients and regression analysis. The sample output of the new dataset and the program which was utilized to develop it and in Appendices C and B, respectively.

Table 4.1 Summary of Factor Subjective Levels and Corresponding Numeric Value Assignment

Name of the Factor	Identification	Subjective Level	Numerical Value
Importance and Accuracy	F1	Low	1
		Medium	2
		High	3
Background Reflectivity	F2	Low	1
		Medium	2
		High	3
Speed	F3	None	1
		Low	2
		Medium	3
		High	4
Size	F4	Fine	1
		Small	2
		Medium	3
		Large	4
Distance of Seeing	F5	Small	1
		Medium	2
		Large	3

Data Analysis

In this section database is analyzed to determine the candidate independent variables, select the form of regression model involving some of these variables, determine the best-fit regression equation, and examine if certain assumptions have been violated. As a result an adequate model satisfying the needs and requirements has been developed.

Correlation Coefficients

Analysis of data to determine the extent of correlation between all the five selected variables and illumination level was performed using CORR procedure in SAS system. The results are included in Appendix C and are summarized in Table 4.2.

Table 4.2 Summary of Results of Correlation Analysis

Name of the Factor (Independent Variables)	Coefficients of Correlation with Illumination Level (Dependent Variable)
Importance and accuracy	0.898
Background reflectivity	0.789
Speed	0.618
Relative size of object	-0.618
Distance of seeing	-0.681

From the results it was found that three factors had positive correlation and two had negative correlation with illumination level requirement for task visibility. It was observed

in the literature and field experience that importance and accuracy desired for a certain task had the strongest effect on the lighting level requirement. As has been shown in Table 4.2 also importance and accuracy has the largest value of the coefficient. It seems logical that if higher accuracy is desired, the illumination level required should also be higher, therefore high positive correlation. Similarly, for factor of speed, when higher speeds are involved for the same task, higher levels of illumination are desired. On the contrary, for relative size of object, the correlation is negative as the requirement of lighting decreases with the increase in size of the object to be seen. However, from the results in the table, the coefficients for background reflectivity and distance of seeing do not follow the trend demonstrated in other studies. With the increase in background reflectivity usually visibility of an object increases, therefore the requirements for higher illumination is not desired and correlation is negative. Similarly, for seeing distance the coefficient is negative but as the distance at which an object of seen increases, illumination level needs to be increased in order to maintain proper visibility hence positive correlation.

This discrepancy can be explained and is introduced by the involvement of importance and accuracy factor. As has been mentioned earlier, importance factor was found to play a critical role in determining illumination levels and often strong enough to undermine the effects of other factors which are not as significant. To examine this effect, correlation analysis was again performed within categories of one importance and accuracy level. It was speculated that by keeping value or level of accuracy and importance factor fixed, the effects of other factors can be more clearly demonstrated. This not only can confirm the logical trend other factors usually follow as regards to lighting requirement but also to reestablish the belief that accuracy and importance of a task is the single most important factor in lighting determi-

nation. The results of further analysis are summarized in Table 4.3. Which gives the correlation of rest of the independent variables with fixed levels of importance.

Table 4.3 Results of Correlation Analysis for Fixed Levels of Importance and Accuracy Factor

Name of the Factor	Correlation with Illumination Level Requirement for Various Levels for Importance and Accuracy		
	Low	Medium	High
Background Reflectivity	-0.70	-0.65	-0.78
Speed	0.81	0.76	0.83
Relative Size of Object	-0.89	-0.79	-0.82
Distance of Seeing	0.76	0.82	0.87

Trial Model Formation

Following correlation analysis data was plotted to see the variation of values of dependent variable for each level of independent variables. This plot presented in Figure 4.6 gives an idea of the data trend to develop of formulate trial models. Various significant independent variables were identified. These variables are candidate variables for model formulation and are listed as follows:

Independent Variable Candidates

1.	Importance and Accuracy	IMP
2	Background Reflectivity	REFL
3.	Speed	SPEED
4.	Relative Size	SIZE
5.	Distance of Seeing	DIST

```
            Plot of LEVEL*F11.  Symbol used is '*'.
            Plot of LEVEL*F22.  Symbol used is '@'.
            Plot of LEVEL*F33.  Symbol used is 'o'.
            Plot of LEVEL*F44.  Symbol used is '#'.
            Plot of LEVEL*F55.  Symbol used is '+'.

   LEVEL |
         |
      80 +
         |  #                             *              o
         |
         |  +              @              *              o
         |
         |
      60 +
         |
         |
         |  o              @              *
         |
         |
      40 +
         |
         |
         |  o              @              *
         |
         |
      20 +  o              *              #
         |
         |
         |  o              *              @
         |  *              o              #
         |  *              @              #              #
       0 +  *              o              o              #
         |
         ---+--------------+--------------+--------------+--
            1              2              3              4

                                 F11
NOTE: 180 obs hidden.
```

Figure 4.6 Plot between Level of Illumination and Factors

Dependent Variable

1. Requirement of Illumination Level LEVEL

The first selection procedure involves performing all possible regressions with the dependent variable and one or more of the independent variables from the list of candidate variables. There are usually two strategies deployed to conduct multiple regression: 1) Stepwise regression procedure (forward technique) and 2) Backward elimination method. The backward elimination method begins with fitting the regression model, which contains all the candidate independent variables. Sum of squares and mean square error are computed for the whole model and the independent variable having the lowest F is dropped. The process is repeated again. Forward selection, on the other hand, involves introducing one variable at a time in the model. The variable which is once entered cannot be eliminated from the regression equation at a later stage.

For this study forward selection method is adopted and trial regression models are developed for different sets of variables. There are five types of models formed in this section, which include single factor models, three factor models, four factor models, and five factor model. The general equation of the models are as below.

1. Single Factor Models

$y = \beta_o + \beta_1 x_1 + \epsilon$

where, y - LEVEL
and x_1 - IMP
or REFL
or SPEED

or SIZE
or DIST

2. Three Factor Models

$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon$
where, y - LEVEL
and x_1, x_2, x_3 - IMP REFL SIZE
IMP REFL SPEED
IMP REFL DIST

3. Four Factor Models

$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \epsilon$
where, y - LEVEL
and x_1, x_2, x_3, x_4 - IMP REFL SPEED SIZE
IMP REFL SIZE DIST

4. Five Factor Model

$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \epsilon$
where, y - LEVEL
and x_1 - IMP
and x_2 - REFL
and x_3 - SPEED
and x_4 - SIZE
and x_5 - DIST

Regression Analysis

Regression analysis for the models selected above was performed using SAS software. PROC REG was utilized for the regression of various one-factor, three-factor, four-factor and five-factor models. The source code of the program used for analysis is included in Appendix B. Since the data is non-experimental, the independent variables are often not truly "independent". The variables are usually correlated with one another to some degree. If these correlations are moderate to high, then the regression coefficients are greatly affected by that particular subset of independent variables in the regression equation. If there are a

number of independent variable, for example in this case, coming up with the best subset can be difficult (58).

To overcome this problem stepwise regression is developed to assist the researchers. The primary goal of stepwise techniques is to take a set of independent variables and put them into a regression one at a time in a specified manner until all variables have been added or until a specified criterion is met. For the regression in this case a STEPWISE technique is used with FORWARD and MAXR selections. Forward technique starts with the best single regressor, then finds the best one to add to what exists etc. MAXR technique tries to find the one-variable regression with the highest R^2, then the two-variable regression with the highest R^2, etc. The results of forward selection procedure for dependent variable are provided in Tables 4.4 through 4.6. Table 4.6 also provides the summary of forward selection procedure for dependent variable LEVEL. The results of maximum R^2 test in selecting model are provided in Tables 4.7 through 4.9. Summary of maximum R^2 is presented later in the chapter.

Testing for Model Adequacy

To test the adequacy of the trial models, results obtained from the regression analysis are analyzed. Figures 4.7 through 4.11 shows the plot between the residuals and the levels values for each best model selected as given by the forward technique and maximum R^2 analysis performed above. The plots were analyzed and compared with the typical residual plots provided in Figure 4.5. Each model was checked for deficiency in data fitting by its trend and scattering. From the figures it can be shown that in each plot from Figure 4.7 to 4.10 the data needed more terms for fitting. Although the plot in Figure 4.10 appears to be

Table 4.4 Forward Selection Procedure for Dependent Variable LEVEL (steps 1 & 2)

Step 1 Variable F11 Entered R-square = 0.80775409 C(p) = 40.33648988

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	14513.60012422	14513.60012422	168.07	0.0001
Error	40	3454.24463768	86.35611594		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-22.24420290	3.18884705	4202.03259309	48.66	0.0001
F11	23.49782609	1.81253607	14513.60012422	168.07	0.0001

Bounds on condition number: 1, 1

Step 2 Variable F33 Entered R-square = 0.86756089 C(p) = 17.96637770

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	15588.19932395	7794.09966197	127.74	0.0001
Error	39	2379.64543796	61.01654969		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-28.15457791	3.02793911	5275.35162759	86.46	0.0001
F11	20.33276922	1.70002582	8728.30020056	143.05	0.0001
F33	6.26204799	1.49216538	1074.59919972	17.61	0.0002

Bounds on condition number: 1.24504, 4.980158

Table 4.5 Forward Selection Procedure for Dependent Variable LEVEL (steps 3 & 4)

Step 3 Variable F44 Entered R-square = 0.89574414 C(p) = 8.48224536

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	3	16094.59171664	5364.86390555	108.83	0.0001
Error	38	1873.25304527	49.29613277		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-8.52889223	6.70093014	79.85974576	1.62	0.2108
F11	17.40215207	1.78073442	4707.82662915	95.50	0.0001
F33	6.45614893	1.34258514	1139.92494314	23.12	0.0001
F44	-5.16021948	1.61001904	506.39239269	10.27	0.0027

Bounds on condition number: 1.690851, 13.07079

Step 4 Variable F55 Entered R-square = 0.90277264 C(p) = 7.61826881

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	16220.87865738	4055.21966434	85.89	0.0001
Error	37	1746.96610453	47.21530012		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-0.95358599	8.02881710	0.66603852	0.01	0.9061
F11	15.61481230	2.05706900	2720.56165864	57.62	0.0001
F33	6.77888581	1.32868002	1229.01896027	26.03	0.0001
F44	-4.12975503	1.69698079	279.62595926	5.92	0.0199
F55	-3.59761516	2.19976790	126.28694074	2.67	0.1104

Bounds on condition number: 2.35578, 29.8529

Table 4.6 Forward Selection Procedure for Dependent Variable LEVEL (step 5)

Step 5 Variable F22 Entered R-square = 0.91165225 C(p) = 5.25961002

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	16380.42608715	3276.08521743	74.30	0.0001
Error	36	1587.41867475	44.09496319		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	3.05466019	8.04002730	6.36501962	0.14	0.7062
F11	19.62812152	2.89885524	2021.59149828	45.85	0.0001
F22	-6.14292075	3.22941976	159.54742978	3.62	0.0652
F33	7.38419922	1.32287021	1373.91960638	31.16	0.0001
F44	-4.43099469	1.64757663	318.93354496	7.23	0.0108
F55	-4.07323496	2.14049136	159.67648119	3.62	0.0651

Bounds on condition number: 5.009379, 75.41855

No other variable met the 0.5000 significance level for entry into the model.

Summary of Forward Selection Procedure for Dependent Variable LEVEL

Step	Variable Entered	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
1	F11	1	0.8078	0.8078	40.3365	168.0668	0.0001
2	F33	2	0.0598	0.8676	17.9664	17.6116	0.0002
3	F44	3	0.0282	0.8957	8.4822	10.2725	0.0027
4	F55	4	0.0070	0.9028	7.6183	2.6747	0.1104
5	F22	5	0.0089	0.9117	6.0000	3.6183	0.0652

Table 4.7 Maximum R-square Improvement for Dependent Variable LEVEL (steps 1 & 2)

Step 1 Variable F11 Entered R-square = 0.80775409 C(p) = 40.33648988

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	14513.60012422	14513.60012422	168.07	0.0001
Error	40	3454.24463768	86.35611594		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-22.24420290	3.18884705	4202.03259309	48.66	0.0001
F11	23.49782609	1.81253607	14513.60012422	168.07	0.0001

Bounds on condition number: 1, 1

The above model is the best 1-variable model found.

Step 2 Variable F33 Entered R-square = 0.86756089 C(p) = 17.96637770

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	15588.19932395	7794.09966197	127.74	0.0001
Error	39	2379.64543796	61.01654969		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-28.15457791	3.02793911	5275.35162759	86.46	0.0001
F11	20.33276922	1.70002582	8728.30020056	143.05	0.0001
F33	6.26204799	1.49216538	1074.59919972	17.61	0.0002

Bounds on condition number: 1.24504, 4.980158

The above model is the best 2-variable model found.

Table 4.8 Maximum R-square Improvement for Dependent Variable LEVEL (steps 3 & 4)

Step 3 Variable F44 Entered R-square = 0.89574414 C(p) = 8.48224536

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	3	16094.59171664	5364.86390555	108.83	0.0001
Error	38	1873.25304527	49.29613277		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-8.52889223	6.70093014	79.85974576	1.62	0.2108
F11	17.40215207	1.78073442	4707.82662915	95.50	0.0001
F33	6.45614893	1.34258514	1139.92494314	23.12	0.0001
F44	-5.16021948	1.61001904	506.39239269	10.27	0.0027

Bounds on condition number: 1.690851, 13.07079
The above model is the best 3-variable model found.

Step 4 Variable F55 Entered R-square = 0.90277264 C(p) = 7.61826881

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	16220.87865738	4055.21966434	85.89	0.0001
Error	37	1746.96610453	47.21530012		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-0.95358599	8.02881710	0.66603852	0.01	0.9061
F11	15.61481230	2.05706900	2720.56165864	57.62	0.0001
F33	6.77888581	1.32868002	1229.01896027	26.03	0.0001
F44	-4.12975503	1.69698079	279.62595926	5.92	0.0199
F55	-3.59761516	2.19976790	126.28694074	2.67	0.1104

Bounds on condition number: 2.35578, 29.8529
The above model is the best 4-variable model found.

Table 4.9 Maximum R-square Improvement for Dependent Variable LEVEL (step 5)

Step 5 Variable F22 Entered R-square = 0.91165225 C(p) = 5.25961002

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	16380.42608715	3276.08521743	74.30	0.0001
Error	36	1587.41867475	44.09496319		
Total	41	17967.84476190			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	3.05466019	8.04002730	6.36501962	0.14	0.7062
F11	19.62812152	2.89885524	2021.59149828	45.85	0.0001
F22	-6.14292075	3.22941976	159.54742978	3.62	0.0652
F33	7.38419922	1.32287021	1373.91960638	31.16	0.0001
F44	-4.43099469	1.64757663	318.93354496	7.23	0.0108
F55	-4.07323496	2.14049136	159.67648119	3.62	0.0651

Bounds on condition number: 5.009379, 75.41855

The above model is the best 5-variable model found.

No further improvement in R-square is possible.

Figure 4.7 Residual Plot of Illumination vs Importance

Figure 4.8 Residual Plot of Illumination vs Importance , Speed

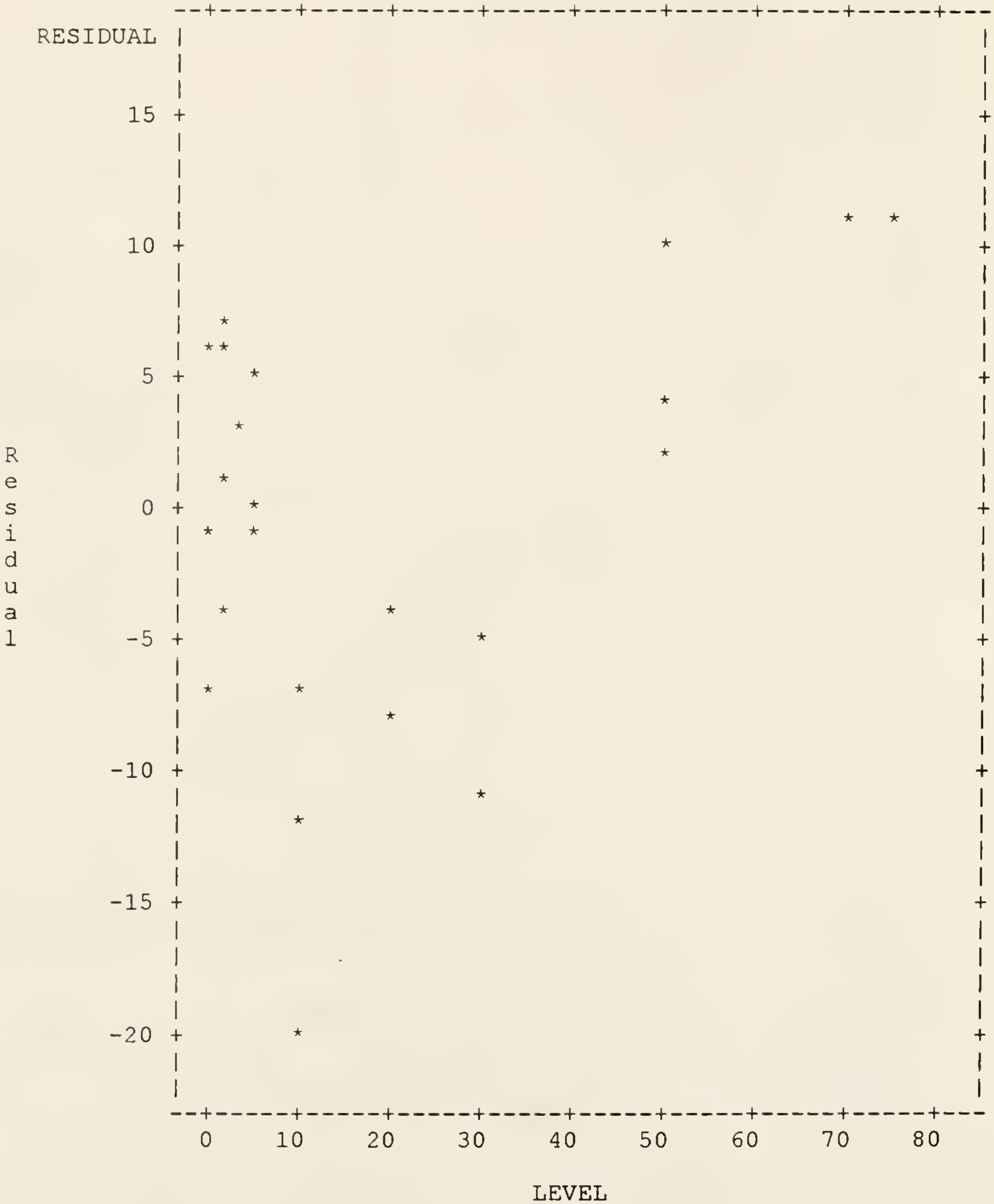


Figure 4.9 Residual Plot of Illumination vs Importance, Speed & Size

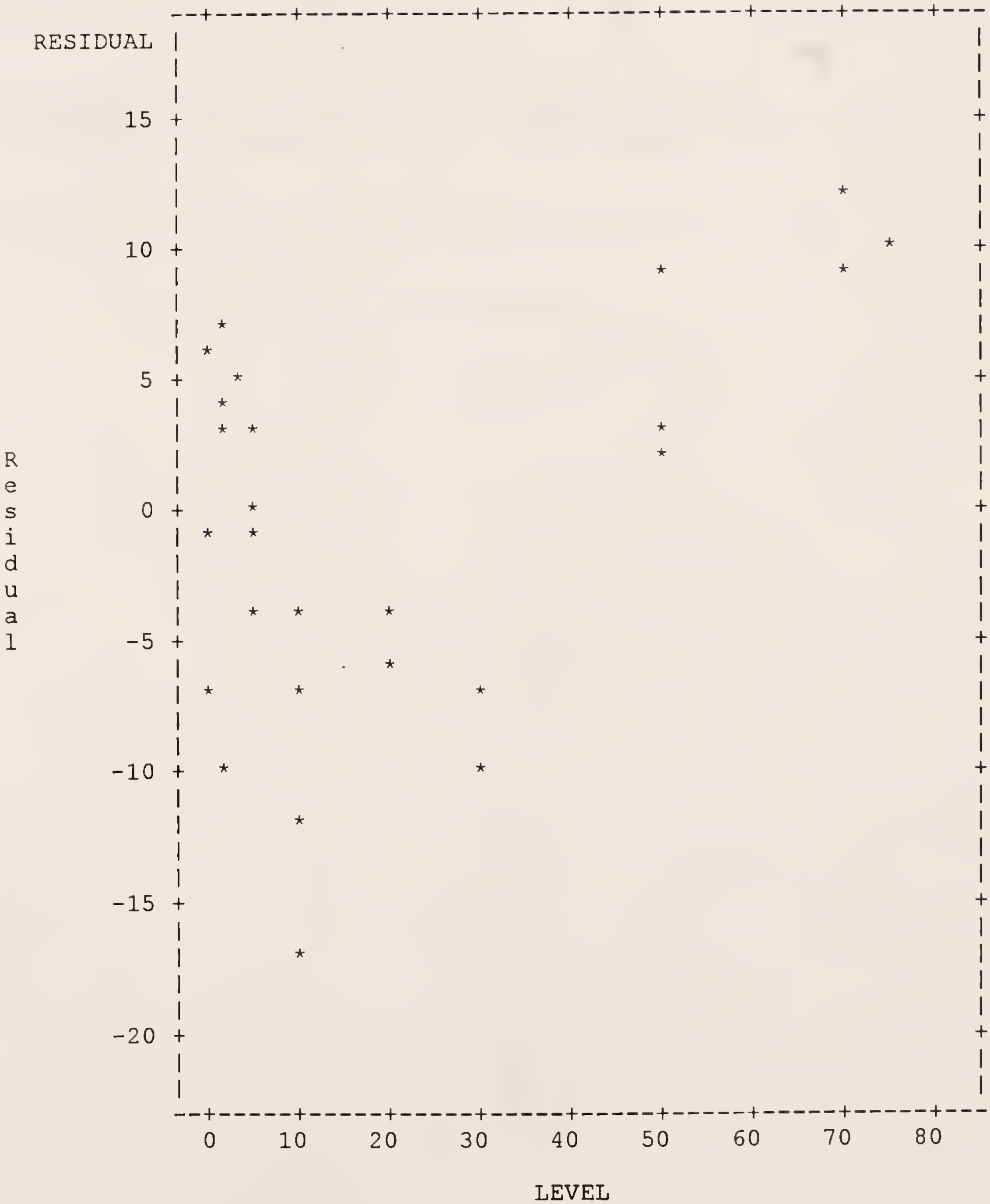


Figure 4.10 Residual Plot of Illumination vs Imp, Speed, Size & Distance

Figure 4.11 Residual Plot of Illumination vs All Five Factors

satisfying the data, another variable was added by the stepwise technique in the regression process to further improve the R^2. Figure 4.11 gives a near perfect fit of the data and random scattering of residuals. The model is considered as adequate and is a evaluated for validity of assumptions.

Model Evaluation and Checking Assumptions

In the regression process, attempts were made to try various independent variable and improve the value of R^2. A summary of C_p values and R^2 are given in Table 4.10 for all the trial models. As can be seen in the table, values of R^2 changed significantly depending on the introduction of one or more variables in the model. As has been pointed out earlier, improvement in R^2 value does not necessarily implies an improvement in the model. Another statistic which is examined for these models was C_p values. These values also varied significantly in the models. However according to Mallow (57), if for a model value of $C_p \approx p$, the number of variables, the model can be considered as the best fit model for the data. From the table, for Model 31 value of C_p is 5.25961, which is very close to the number of total variables in the model and value of R^2 is also highest. Hence this model is selected as the final model. All the assumptions for this model are checked to examine the validity.

The multiple regression analysis involves four fundamental assumptions for the model. Since the assumptions are written in terms of the random errors, it is important for any chosen model to check these assumptions by using residuals which are estimates of random errors. To examine the validity of these assumptions various tests were performed. The first assumption of zero expectation deals with model selection and if additional independent variables need to be included in the model. Usually if adequate variables are identified and

Table 4.10 Results of Different Regression Models

S No.	C(p)	R-square	No. of Variables	Variables in Model
1	40.33649	0.80775409	1	F11
2	115.34394	0.62367799	1	F22
3	213.90962	0.38178753	1	F33
4	213.51875	0.38274678	1	F44
5	180.22888	0.46444358	1	F55
6	17.96638	0.86756089	2	F11 F33
7	32.33384	0.83230165	2	F11 F44
8	38.20332	0.81789733	2	F11 F55
9	42.33148	0.80776639	2	F11 F22
10	94.77640	0.67906109	2	F22 F44
11	95.64812	0.67692180	2	F22 F55
12	87.60308	0.69666516	2	F22 F33
13	83.23338	0.70738885	2	F33 F55
14	113.24788	0.63373016	2	F33 F44
15	153.88757	0.53399613	2	F44 F55
16	8.48225	0.89574414	3	F11 F33 F44
17	11.95972	0.88721006	3	F11 F33 F55
18	18.59738	0.87092056	3	F11 F22 F33
19	33.49036	0.83437162	3	F11 F44 F55
20	34.08192	0.83291988	3	F11 F22 F44
21	40.09874	0.81815397	3	F11 F22 F55
22	57.95178	0.77434075	3	F22 F33 F55
23	63.29807	0.76122040	3	F22 F33 F44
24	87.64646	0.70146691	3	F22 F44 F55
25	67.31606	0.75135984	3	F33 F44 F55
26	7.61827	0.90277264	4	F11 F33 F44 F55
27	7.62120	0.90276546	4	F11 F22 F33 F44
28	11.23288	0.89390201	4	F11 F22 F33 F55
29	35.15820	0.83518678	4	F11 F22 F44 F55
30	49.84631	0.79914062	4	F22 F33 F44 F55
31	5.25961	0.91165225	5	F11 F22 F33 F44 F55

included in the model, this assumption is satisfied. In this case since Model 31 involves all the selected independent factors, this assumption holds. The second assumption of constant variances was examined by testing the plot of predicted and residual values. The results are shown in Table 4.11, which provides listing of residual and predicted values for each observation. The plot of these values is shown in Figure 4.12. It is clear from the figure that the trend is not similar to the fourth plot in Figure 4.5, which checks unequal variances. On the other hand the random scattering of points indicate that the regression equation appropriately fits the data. The third assumption is of normality of random errors. This assumption is usually checked by a histogram or stem-and-leaf plot to determine any skewness in the distribution. Since random errors are assumed to be normally distributed around mean, this assumption is checked by plotting the residuals in a normal curve form. Figure 4.13 shows the plot which is very close to normal except few outliers. This confirms the validity of the third assumption. The fourth assumption is that the random errors are statistically independent, and hence uncorrelated. This assumption is checked by the plotting the residuals in a time sequence. But since in this data no time variations were involved, question of examining plot of residuals versus time for testing any serial correlation did not arise.

Table 4.11 Predicted and Residual Values of LEVEL

Obs	LEVEL	Predicted	Residual
1	50.0000	51.4864	-1.4864
2	50.0000	37.9592	12.0408
3	75.0000	64.5428	10.4572
4	0.5000	-6.0196	6.5196
5	1.5000	-6.0196	7.5196
6	5.0000	5.7956	-0.7956
7	30.0000	39.6712	-9.6712
8	5.0000	5.7956	-0.7956
9	10.0000	11.8966	-1.8966
10	5.0000	6.9156	-1.9156
11	3.0000	-1.5886	4.5886
12	1.0000	-6.0196	7.0196
13	5.0000	5.7956	-0.7956
14	5.0000	6.9156	-1.9156
15	3.0000	-1.5886	4.5886
16	5.0000	5.7956	-0.7956
17	1.0000	-6.0196	7.0196
18	20.0000	23.3540	-3.3540
19	2.0000	7.7991	-5.7991
20	5.0000	6.9156	-1.9156
21	2.0000	-1.9464	3.9464
22	0.4000	8.7488	-8.3488
23	0.2000	1.3646	-1.1646
24	0.1000	1.3646	-1.2646
25	0.5000	-6.0196	6.5196
26	5.0000	2.4846	2.5154
27	10.0000	20.4008	-10.4008
28	20.0000	24.8318	-4.8318
29	70.0000	62.1815	7.8185
30	30.0000	42.9821	-12.9821
31	50.0000	44.2234	5.7766
32	70.0000	60.1118	9.8882
33	20.0000	23.3540	-3.3540
34	20.0000	23.3540	-3.3540
35	0.4000	8.7488	-8.3488
36	3.0000	-1.5886	4.5886
37	5.0000	9.8688	-4.8688
38	2.0000	-1.9464	3.9464
39	10.0000	15.9698	-5.9698
40	5.0000	5.7956	-0.7956
41	1.0000	-1.5886	2.5886
42	10.0000	20.5220	-10.5220

Figure 4.12 Plot of Residual and Predicted Values

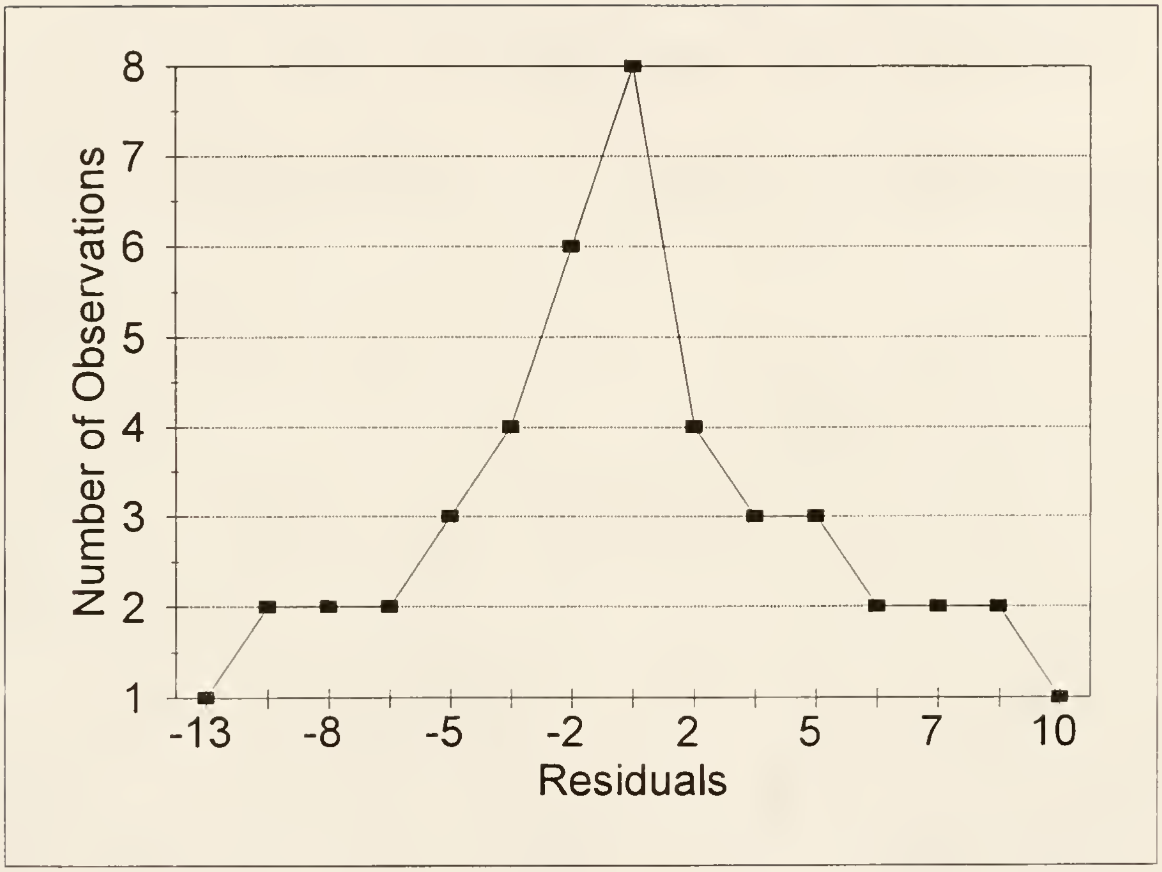


Figure 4.13 Distribution of Residuals

From SAS analysis the values of the parameters and intercept for the model are determined. The regression model which fits the data is given as follows:

LEVEL	=	19.628122	x	IMP
		-6.142921	x	REFL
		+7.384199	x	SPEED
		-4.430995	x	SIZE
		-4.073235	x	DIST
		+3.054660		

Summary

In this chapter an introduction to model approach was given and the model development was performed. Various regression models and techniques such as least square and correlation were introduced. Discussion also included linear and multiple regression. Various criteria to evaluate the model were also discussed, which included residual analysis, lack-of-fit test, coefficient of determination, Mallows' statistic, and hypothesis testing. It was determined that a model having highest coefficient of determination and Mallows' C_p value equal to the number of parameters can best fit the data. Residual analysis can be performed to test the underlying assumptions of multiple regression. Fundamental assumptions were also discussed. The discussion also included a brief introduction to various SAS procedures utilized in this study.

For analysis database was developed in SAS. Various correlation analysis procedures

were used to determine the degree of correlation and significance of various independent factors. Trial models were formulated based on the results of correlation analysis. Regression was performed for these trial models. A stepwise forward selection process was chosen to determine the maximum R^2. The results for best model in each category of one, two, three, four, and five-factor models were obtained. These models were then tested for their adequacy by plotting the residuals versus the dependent variable. Selected model was then evaluated for its validity of fundamental assumptions. The Model 31 involving five factors, having highest R^2, and $C_p \approx p$ was chosen as the best fit regression line. The model also satisfied all the basic assumptions.

CHAPTER 5
DEVELOPMENT OF GUIDELINES

Introduction

In this chapter an attempt has been made to develop illuminance levels categories and guidelines for nighttime highway work. To be consistent with the industry practice of lighting design and recommendations format for the categories has been adopted from IES categories. IES categories and recommendations take into account not only the performance and safety aspects but also the energy concerns and other human needs such as attractive work places. Therefore the adopted format also inherently include these characteristics.

Following the development of categories for construction work, various guidelines are developed with the assistance of experts in field, opinions of crew, and comparison with non-highway task matrix. There has also been an attempt to include guidelines for equipment along with the task illumination levels. For equipment two major classifications is done one for slow-moving equipment and other for fast-moving equipment and glare control criteria is also included in the guidelines.

Development of Illuminance Levels Categories

Development of Guidelines is done for illuminance levels and not for luminance levels. The purpose of lighting design, guidelines and categories is to provide energy efficient

illumination in quality and quantity sufficient for safety and to enhance visibility and productivity within a pleasant environment. In the following section IES illuminance categories and presented and similar categories for highway night work are adopted.

IES Categories

IES adopted the policy of recommending illuminance in ranges, replacing the previously recommended single values for specific task in 1979. These ranges were derived by consensus from many individuals in North America and in other countries in the world. The standard describes the illuminance range method. In addition, representatives of certain industries have established tables of single illuminance values, in their opinion, represent appropriate illuminances for the listed tasks and may be used in preference to the illuminance range method (8).

The desirable illuminance for a space depends primarily upon the use of that space - the seeing tasks, the workers, and the importance of speed and accuracy in performing the tasks. Illuminance recommendations for tasks and spaces are given in Table 5.1. Recommendations are in illuminance categories (letters A through I) and their associated illuminance value ranges. The values given are considered to be target maintained illuminance. Table 5.1 contains the recommended illuminance categories for many commonly occurring industrial tasks. For any task, choose a listed task that closely resembles the one in question. Select one that has similar contrast and degree of visual difficulty. If there is more than one task and they require different illuminances, the designer must choose between them. There are several alternative methods for combining many criteria in the handbook (8).

The target values of illuminance for Categories A to C refer to average maintained

Table 5.1 IES Illuminance Categories Recommended for Tasks and Spaces

Type of Activity	Illuminance Category	Ranges of Illumination (foot-candle)	Reference Work plane
Public spaces with dark surroundings	A	2-3-5	General lighting throughout spaces
Simple orientation for short temporary visits	B	5-7.5-10	
Working spaces where visual tasks are only occasionally performed	C	10-15-20	
Performance of visual tasks of high contrast or large size	D	20-30-50	Illumination on task
Performance of visual tasks of medium contrast or small size	E	50-75-100	
Performance of visual tasks of low contrast or very small size	F	100-150-200	
Performance of visual tasks of low contrast and very small size over a prolonged period	G	200-300-500	Illuminance on task, obtained by a combination of general and local (supplementary lighting)
Performance of very prolonged and exacting visual tasks	H	500-750-1000	
Performance of very special visual tasks of extremely low contrast and small size	I	1000-1500-2000	

Source: Ref. 8

illuminance values. The lumen method, using zonal-cavity calculated coefficients of utilization for luminaires or for daylighting, predicts such average values for categories A to C. Illuminance values for categories E to I are maintained illuminance on and in the plane of the task and point calculation methods are appropriate. The procedure for determining light loss factors should always be used in calculating maintained average or point illuminance. Illuminance levels for individual tasks should be increased where workers wear eye-protective devices with occupationally-required tinted lenses that materially reduce the light reaching the eye.

Nightwork Illuminance Level Categories

The prime requirement for highway construction lighting is to facilitate the performance of construction-related visual tasks in the workzone through high-quality illumination. Correct lighting can enable the crew to observe and effectively control various equipment and processes in highway operations. Based on the appraisal of findings, recommendations for illuminance categories and values are provided in Table 5.2. The five categories, which provide for average maintained illuminance level ranges as less than 5 fc (54 lx), 5 to 10 fc (108 lx), 10 to 20 fc (216 lx), 20 to 30 fc (324 lx), and more than 30 fc for various tasks, cover majority of the highway and bridge related maintenance and construction operations. Although the recommended levels satisfy safety requirements, they are also intended to provide a guide for efficient visual performance. For this reason they may not be interpreted as recommended requirements for regulatory minimum illuminance.

Determination of the three categories and their minimum illuminance values was influenced by several factors. The significant factors include

Table 5.2 Recommended Illuminance Ranges and Categories for Nighttime Highway Construction and Maintenance Tasks

Category	Min Illuminance Level foot-candle	Area of Illumination	Type of Activity	Example of Areas and Activities to be illuminated
I	less than 5	general illumination throughout spaces	performance of visual task for large objects; or medium contrast; or for general safety requirements	a) Excavation b) Sweeping & cleanup c) Movement area in workzone
II	5 to 10	general illumination of tasks and around equipment	performance of visual task for medium objects; or low to medium contrast; or low desired accuracy ; or for safety on and around equipment.	a) Barrier wall b) Milling c) General Concrete work d) Around paver, miller & other construction equipment
III	10 to 20	illuminance on task	performance of visual task for small objects; or low contrast; or desired medium accuracy.	a) Resurfacing b) Specific concrete work attention
IV	20 to 30	illuminance on task	performance of visual task of fine sizes; or very low contrast; desired high accuracy and good finish.	a) Bridge screed finish b) Surface finish c) work requiring extreme caution
V	more than 30	illuminance on task	performance of visual task of very fine sizes; or extreme low contrast; or desired high accuracy and very fine finish.	a) Fine surface finish b) Crack filling c) Signalization or similar work requiring extreme attention.

1) IES recommended minimum levels for normal activity from the point of view of safety. For visual detection in high hazard situations this value is 5 fc (54 lx).

2) IES recommended levels and uniformity ratios for construction activities, which is 10 fc (108 lx) for general construction and 2 fc (22 lx) for excavation work.

3) OSHA required minimum illumination intensities for construction industry, which ranges from 3 fc (33 lx) to 10 fc (108 lx) for various construction activities.

4) Proposed 30 CFR regulations for illumination requirements for draglines, shovels and wheel excavators, which range from 5 fc (54 lx) to 10 fc (108 lx) for various parts of the equipment.

5) Provisions for lighting requirements and guidelines as included in various state specifications for highway and bridge work. Minimum of 5 fc (54 lx) in Florida, 10 fc (108 lx) in Michigan, 10-20 fc (54-108 lx) in North Carolina, and 20 fc (216 lx) in Maryland are some of the provisions.

6) Opinions and views of various experts as obtained from the questionnaire survey and literature review concerning comfortable and practical minimum illuminance values and categories for nighttime highway work.

7) Result of experiences of the research team as obtained from the field reviews and interviewing crew personnel.

As contrast to IES illuminance ranges and weighing-factor system, the suggested categories in Table 5.2 recommend only the average maintained illuminance values. In 1979, IES shifted from single value recommendation to the range system to reflect lighting-performance trends found in research. It was intended that the new procedure would allow flexibility in determining illuminance levels to the designer to effectively use the range approach depending

on lighting task characteristics. The characteristics for lighting task included: 1) visual display or details to be seen, 2) age of the observers, 3) importance of speed or accuracy for visual performance, and 4) reflectance of the task and background.

The object in the visual display offers some inherent visual difficulty and affects the illuminance value required to perform the visual task. As pointed out in the previous chapter, the age of the observer reflects the condition of visual system. For typical highway operations nearly all the crew and equipment operators can be classified in one broad age category and, therefore, age is assumed to cause no additional variations on the illuminance values other than the ones selected for that age-group. The importance of speed and accuracy depends on the seeing requirements, whether casual, important or critical. The reflectance of the object and background in a task determines luminance caused by the illuminance. However, from the analysis of findings it was found that reflectance for various road and other construction surfaces does not vary significantly.

As a result the five recommended categories were found to be adequate to account for differences in visual display and variations in accuracy and speed for the majority of the highway construction tasks. Another reason to limit the number of categories or illuminance levels to three is attributed to the feasibility of attaining one or more levels in one operation.

Category I is recommended for the general illumination throughout spaces in the workzone primarily from the safety point of view, in the area where crew movement is expected or taking place. This category is also recommended for tasks involving performance of visual task of large sizes and high contrast. Typical tasks appropriate for this category are excavation, sweeping, clean-up, and general movement in the workzone area.

Category II is recommended for illumination of general spaces, and on and around

construction equipment including the visual tasks associated with the equipment. The primary concern in suggesting the minimum illuminance value for this category is equipment safety and low to medium accuracy desired for the task. For certain tasks such as barrier wall and milling not only is the visual requirement crucial but safety around construction equipment and miller is also important. This category is appropriate for other medium sized and medium contrast tasks.

Category III is suggested mainly because of the efficient visual performance required for certain tasks. Highway tasks which require medium accuracy, small sizes of visual tasks, and low contrast can be included in this category. Resurfacing and specific concrete work are some of the examples.

Category IV is suggested as the average illuminance level to be maintained on tasks requiring high degree of finish and fine sizes. Tasks with low contrast can also be included in the category. Some of the example are bridge screed finish and other surface finishes. Construction works requiring extreme caution can also be included in this category.

Category V is suitable for those tasks which present higher visual difficulty and require increased attention from the observer. Such tasks include crack and pothole filling, joint sealing, critical connections, and tasks involving maintenance of electrical connections and moving mechanical parts. Other tasks requiring very fine finish and involving extremely fine sizes and contrasts can be covered in this category. There is no upper limit for the range in this category, which may be decided by the designer as seemed necessary.

Recommended Illumination Level Categories for Nightwork Activities

As described in chapter 3, a similar assignment of factor levels was also performed for all the identified highway construction and maintenance tasks. The matrix developed in the chapter 3 for non-highway tasks was taken into consideration for comparison. The statistical analysis of the non-highway matrix in chapter 4 revealed a correlation between the factors and their affect on illumination levels. Importance and accuracy required for a task had the most significant effect on illumination levels. As a result of the analysis, it was determined that if four or more factors including importance and accuracy match with the factors of another task, the illumination level recommended for the first task may be suggested for the second task also. The output is included in Appendix D.

For each of the highway tasks, four or more factors from non-highway matrix were matched. A program in SAS was written to conduct the analysis. An average of illumination levels specified for all matching non-highway tasks was utilized to suggest illumination categories for highway tasks. Table 5.3 shows the typical highway tasks, their factor description, averages obtained from comparison with non-highway matrix, and suggested illumination categories. The suggested illumination level categories are assigned to satisfy minimum requirements for a particular task and are based in part on the average of illumination levels of equivalent non-highway tasks.

Table 5.3 gives the corresponding category for each task and usually the median value of the category should be used as average maintained illumination on the task or in the spaces. The problem however arises if in a certain operation there are more than one task that require different illuminances. The illumination requirements maybe satisfied by the use of variable

Table 5.3 Suggested Illumination Categories and Levels for Typical Highway Construction and Maintenance Tasks

Task No.	Task Description (Construction)	Factors					Average Levels (foot-candle)	Suggested Category
		Imp.	Refl.	Spd.	Size	Dist.		
1.	Excavation - regular, lateral ditch, channel	L	L	N	L	L	1.3	I
2.	Embankment, Filling and Compaction	L	L	M	L	L	0.6	I
3.	Barrier Walls, Traffic Separators	M	M	N	M	L	10	II
4.	Milling and Removal	M	M	M	M	L	10	II
5.	Resurfacing	M	H	M	L	L	11	III
6.	Concrete Pavement construction	M	H	L	M	L	12	III
7.	Subgrade stabilization & construction	L	L	L	L	M	1.86	I
8.	Base Courses - clay, cement, asphalt	M	L	M	M	L	10	II
9.	Surface treatment	M	H	M	L	L	10	II
10.	Waterproofing/ Sealing	M	H	M	M	M	10	II
11.	Sidewalks	M	M	L	L	M	20	III
12.	Riprap	M	M	L	M	M	17.5	III
13.	Guardrail, Fencing	M	M	N	M	M	15.7	III
14.	Painting Stripes/Markers/Metal Buttons	M	H	M	S	L	10	II
15.	Landscaping, Grassing, Sodding	L	L	N	L	L	1.3	I
16.	Highway Signing	M	M	N	M	M	15.7	III
17.	Traffic Signals	H	M	N	S	S	43.3	V
18.	Highway Lighting System	H	M	N	S	M	70	V
19.	Bridge Decks	M	L	N	M	M	10	II
20.	Drainage Structures, culverts, storm sewers	M	M	N	L	M	13.3	III
21.	Other Concrete Structures	M	H	L	M	L	10	II
	(maintenance)							
22.	Maintenance of earthwork/ embankment	L	L	M	L	L	0.6	I
23.	Reworking Shoulders	L	H	M	L	L	0.4	I
24.	Repair of Concrete Pavement	M	M	M	S	M	10	II
25.	Crack filling	H	M	L	F	M	30	IV
26.	Pot filling	M	M	N	F	M	13.3	III
27.	Resetting Guardrail/ fencing	M	M	N	M	M	15.7	III

lighting system. For example, by designing for the highest level and providing switching capabilities to adjust for the other tasks. However in certain construction situations this may not be practically possible. For approaches in which lighting level are set equal to the requirements for the task needing the highest illuminance, care should be taken to avoid selecting tasks that are relatively unimportant or not performed frequently. An aggregate illuminance value may be developed by averaging individual task recommendations. A more sophisticated approach is to develop a time spent and importance approach for the task and determine levels.

Developing Equipment Guidelines including Glare Criteria

In order to recommend guidelines for equipment lighting, a set of construction equipment most commonly used for highway work was selected. Based on the equipment's characteristics, its application and relevant Society of Automotive Engineers (SAE) current practices, a minimum area to be illuminated in front and back of the equipment is recommended.

The current SAE recommended practice J1024 for forward lighting on construction and industrial machinery provides for adequate illumination for a distance that exceeds the vehicle stopping distance at its maximum operating speed (59). This stopping distance includes a 1.5-second operator reaction time interval and can be computed by the following formula:

$$D\ (\text{ft}) = 2.2 \times \text{mph}$$

$$D\ (\text{m}) = 0.4167 \times \text{km/h}$$

The actual stopping distance is a function of machine mass and speed. Braking performance for rubber-tired construction machines is provided as a recommended practice in SAE J1142 (59). At typical working speeds on the order of 10-15 mph, braking distances are approximately 15-20 ft plus the reaction distance of 33 ft. The illuminated area in the direction of travel should, therefore, be approximately 58 ft ahead and behind the equipment. Although SAE standards do not provide an illumination level for this point, it is estimated that at the maximum range the illumination should be at least 1 fc (10.8 lx).

The suggested minimum area to be illuminated for each piece of equipment is presented in Table 5.4. For practical reasons, most of the equipment is classified in two broad categories: 1) slow-moving equipment, and 2) fast-moving equipment. Although the illumination level at the maximum range provided in the table should be not less than 1 fc, the task illumination levels around the equipment should conform to the categories and minimum levels recommended for various tasks.

To determine the optimum configuration of lights on various equipment in order to achieve minimum lighted area as required in Table 5.4, help of a lighting software was taken. Advanced Graphics Interface (AGI), the lighting software, is one of the popular and easy-to-use software for design in lighting industry. It provides various facilities to create 3-dimensional graphics, assign obstructions and shapes, define lights and their characteristics, locate lights required, and determine iso-candela lines for a given plane of calculation.

Table 5.4 Recommended Illuminated Area in the Direction of Travel for Various Construction Equipment

Type of Equipment	Working Speed (mph)	Reaction Distance[a] (ft)	Braking Distance (ft)	Area to be Illuminated in Front and Back of Equipment[b] (ft)
Slow-Moving Equipment				
Paver Milling Machine	4-5	11	5	16
Fast-Moving Equipment				
Backhoe Loader Wheel Tractor Scraper Wheel Loader Compactor/Roller Motor Grader	10-15	33	15-25	58

[a] Reaction distance = 2.2 x working speed
[b] Area to be illuminated = reaction distance + braking distance

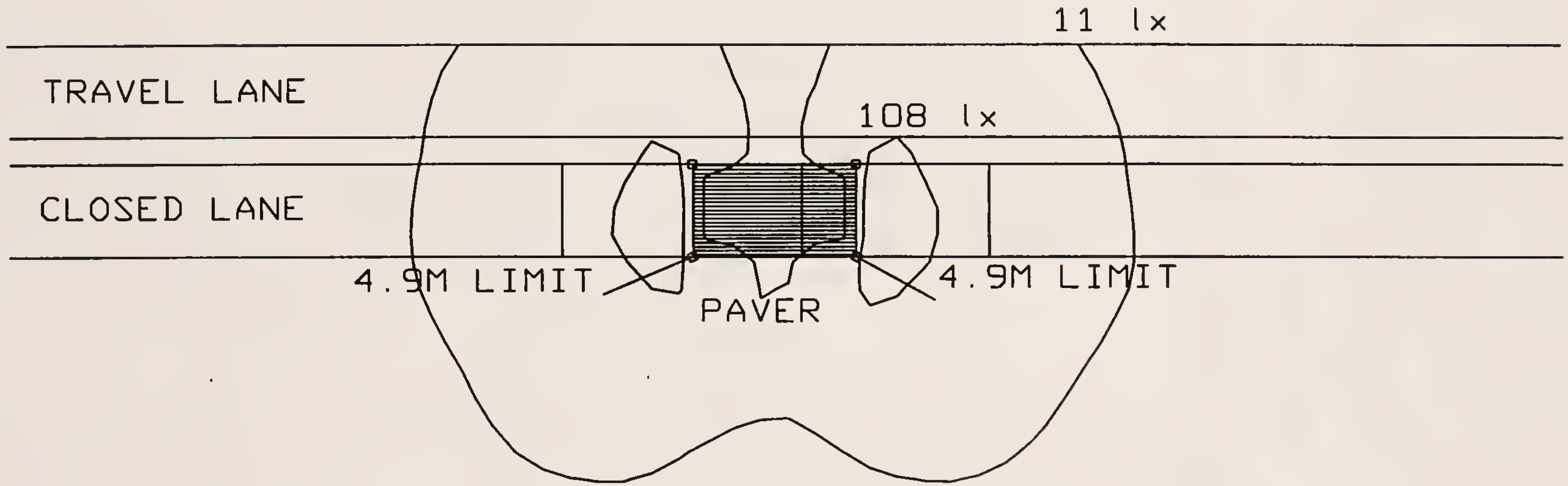
For the purpose of determining optimum configuration, a number of simulations were performed on AGI. Since all the equipments are categorized into slow-moving and fast-moving categories, simulations were performed for two sets of equipment. For lights, the most commonly used Quartz retrofit lights were utilized. During field investigation it was observed that equipment mounted quartz lights usually had the range of power from 500 watt to 1000 watt. Simulation was done for all the ranges with varying height, orientation and tilt

(angle of beam from the vertical) of the lamps. The objective of the experimentation was to achieve 1 fc specified level at the farthest points in front and at the back of the equipment as required by Table 5.4. Results of simulation for slow-moving equipment and fast-moving equipment are shown in Figure 5.1 and 5.2, respectively. The figures also indicate 1 fc and 10 fc iso-lines, limits of minimum level requirements, lamp aiming and orientation and a table block which gives the rest of the details not so evident in the graphics.

Consideration of Glare Criteria

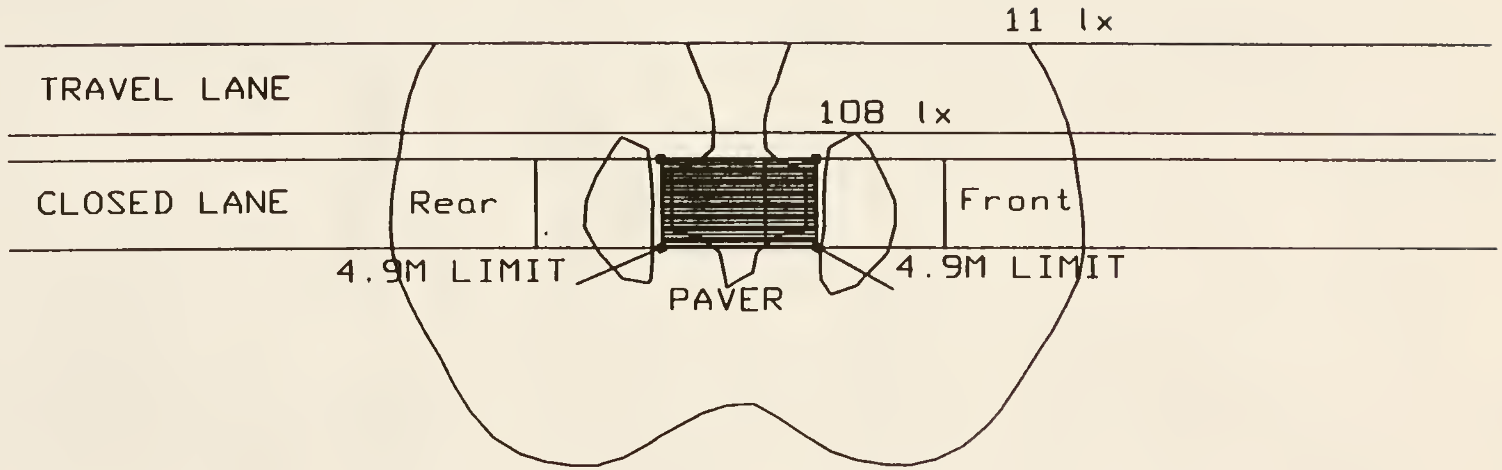
It has been noted in the findings that glare hazard, both disability and discomfort, is a serious problem on highways. The various sources of glare affecting the crew and the motorists include: 1) glare from headlights of travelling vehicles to the crew, 2) glare from light plants to the crew, 3) glare from light plants to the motorists, and 4) glare from equipment retrofit light to the crew and the motorists. Since the intensity of the equipment headlights was not found to be high, glare from these lights to the construction workers and travelling public was limited. However, headlights of the vehicles and equipment retrofit lights can produce significant glare. Glare caused by the stationary light plants can be the most severe for both workers and motorists.

There are several methods which have been suggested to evaluate and quantify glare. As described in findings, these methods include: 1) BCD luminance, 2) Glare Control Mark, and 3) Visual Comfort Probability. These methods can be utilized and acceptance levels can be specified for certain fixed and stationary type of settings. However, it is difficult to specify



EQUIPMENT	Paver			
CATGEORY	Slow Moving Equipment			
MIN. ILLUMN.	11 lx (1 fc) at 4.9m (16ft) limits			
LIGHT PLANT	FRONT_R	FRONT_L	REAR_R	REAR_L
HEIGHT	3.3m	3.3m	3.5m	3.5m
LAMP (QTZ)	500 w	500 w	500w	500w
TILT (deg)	45.0	45.0	45.0	45.0
ORIENTATION	331.0	0	203.0	180.0

Figure 5.1 Results of AGI Simulation for Lighting Configuration of Slow Moving Equipment



EQUIPMENT	Paver			
CATGEORY	Slow Moving Equipment			
MIN. ILLUMN.	11 lx (1 fc) at 4.9m (16ft) limits			
LIGHT PLANT	FRONT_R	FRONT_L	REAR_R	REAR_L
HEIGHT	3.3m	3.3m	3.5m	3.5m
LAMP (QTZ)	500 w	500 w	500w	500w
TILT (deg)	45.0	45.0	45.0	45.0
ORIENTATION	331.0	0	203.0	180.0

Figure 5.2 Results of AGI Simulation for Lighting Configuration of Fast Moving Equipment

and achieve such levels considering the dynamics of highway construction workzone. Instead a more practical approach of controlling glare has been adopted in this study. This approach includes: 1) avoiding glare from the vehicle headlights to the crew in the workzone, and 2) reducing glare from the light plants to the motorists.

To avoid glare to the workers from the headlights of the travelling vehicles, several measures can be taken. However, the most viable solution exists in protecting the workzone from the travelling lanes. Usually glare avoidance screens or barrier walls are used as a measure to protect workers from outside glare. Table 5.5, obtained as a result of survey, provides a summary of various states utilizing screens or barrier to control glare. Often height of the barrier walls was not thought to be sufficient to completely protect the workzone from vehicle lights. As a result several states mounted additional screens, panels or paddles on the barrier walls to help separate the lanes and reduce glare.

In order to limit the glare from stationary tower light plants to the motorists, appropriate lighting configuration was determined to be a viable solution. In some cases the motorist may be protected from the workzone lighting by providing screens on top or by mounting lamps below the top edge of the barrier wall. However, in the most general case where light sources are elevated, glare hazard can be most efficiently controlled by selecting an appropriate configuration and controlling the beam angle. Figure 5.3 illustrates the relevant geometry between light source and the observer. Beam angle is measured as the angle between the center line of beam and vertical and eccentricity is given by angular distance of the light source from the line of sight of the observer. According to a study amount of glare decreases or BCD luminance increases as beam angle decreases and eccentricity increases (8). Figure 5.4 shows the result of the study for three beam angles (0, 45 and 60 degrees). How-

Table 5.5 Utilization of Glare Avoidance Screens and Barriers by Various States

Name of the State	Screens or Barriers utilized to aviod glare to motorists
California	2 ft high plywood "GAWK" screens mounted on concrete barrier walls K-rail used by the contractors for maintenance work.
Georgia	Plywood paddles on concrete barrier walls for apparent glare problem.
Illinois	Screens used usually at crossovers and curves.
Iowa	TBR mounted glare screens to help separate lanes.
Kansas	Sometimes Jersey barriers are utilized.
Kentucky	Concrete barrier walls.
Maine	Concrete barriers on bridge decks.
Maryland	Modeular units consisting of vertical blades mounted on a continous horizontal base rail.
Missouri	Concrete barrier walls.
Nevada	Vertical panels generally used at curves.
New York	Fabric screens are utilized based on contractor's discretion.
Oklahoma	Median barrier with blade type portable modular glare screen.
Rhode Island	24 inches high Modular Guidance System on top of Jersey barrier.

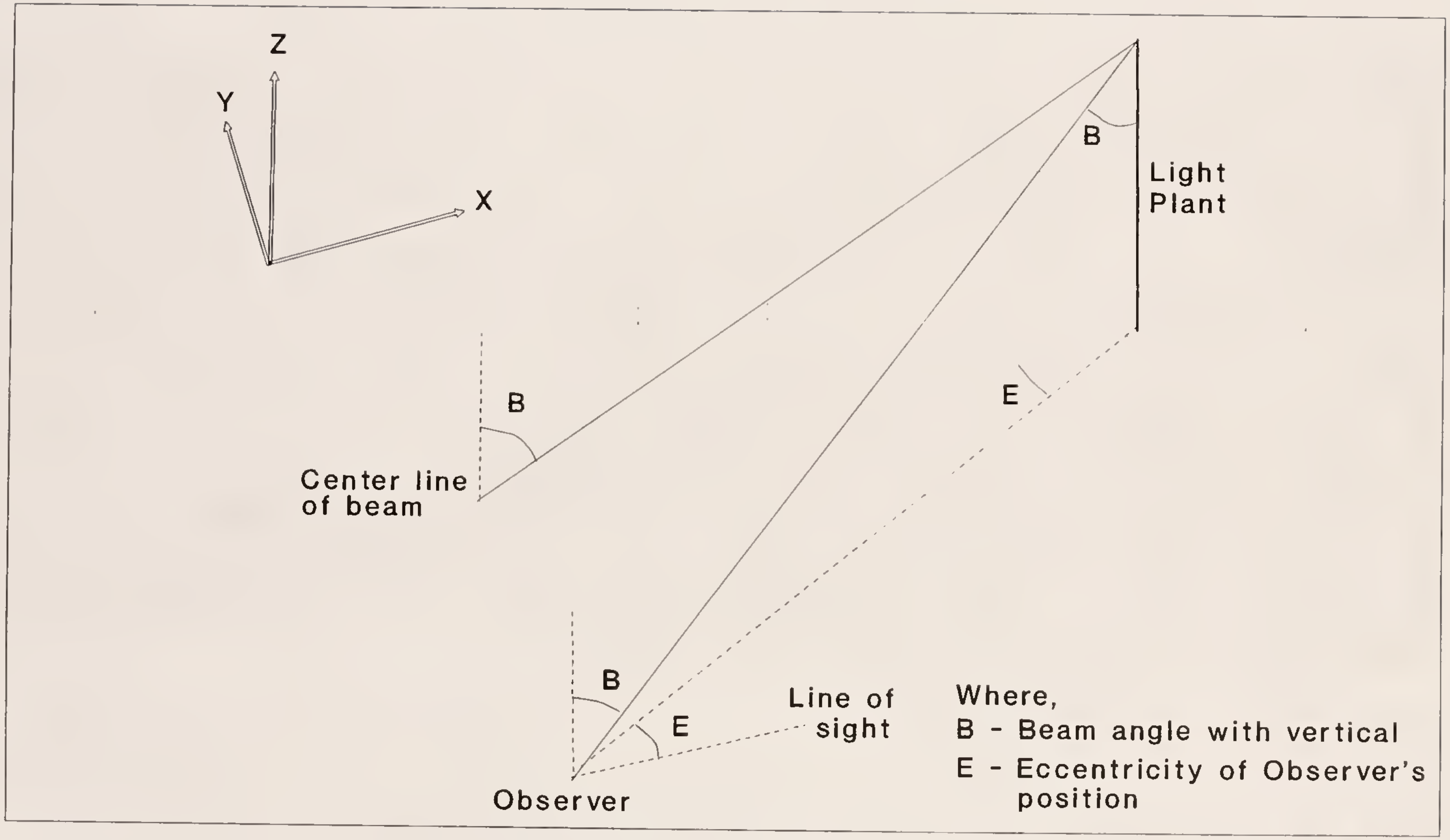


Figure 5.3 Effect of Beam Angle and Eccentricity in Reducing Glare

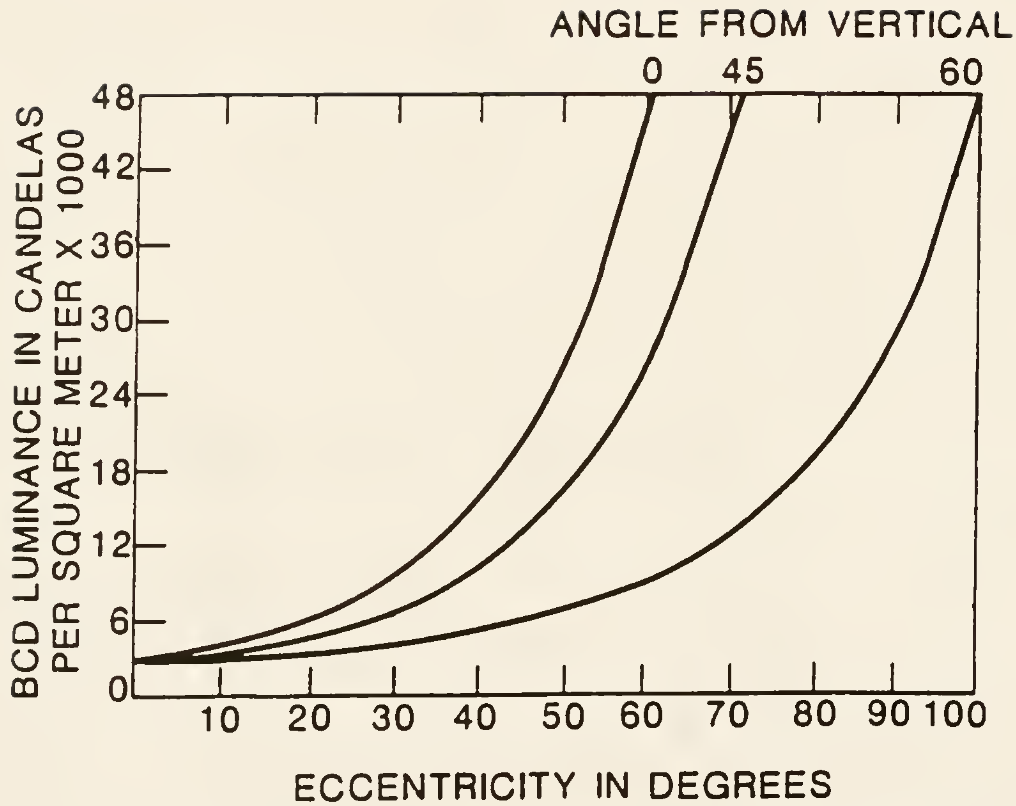


Figure 5.4 BCD Luminance for Glare Sources at Various Angular Distance from the Line of Sight

ever for a typical highway workzone situation, maximum eccentricity is limited and cannot exceed the total width of a few lanes. As a result, beam angle is the only controlling factor available for glare control.

Beam angle, if reduced substantially, can cause significant adverse effects on beam spread, area of illumination and uniformity. A beam angle of not more than 60 degrees for elevated flood lights is most appropriate and also appears to agree with several state highway agencies specifications. The maximum height of the tower for this beam angle is limited to 30 ft.

Table 5.6 summarizes the results for both the categories of equipment and specifies at least one set of height, tilt, orientation and power of the lamps for each category to obtain minimum recommended levels at given distances. The guidelines specified in Table 5.6 also takes into account the glare control criteria and for this reason tilt angle is always equal to or lower than 60 degrees. Lamp heights in the table are given from the ground, therefore, mounting heights on various equipment is a function of actual equipment height and can be determined by subtracting equipment height from the given lamp heights. Lamps for these guidelines are considered as quartz lamps of 500 watt power with a parabolic or rectangular reflective case covering.

Summary

In this chapter illuminance level categories recommended by IES for indoor and outdoor spaces and tasks were discussed. Based on the recommendations, opinions of knowledgeable individuals, and state survey responses illuminance level categories were suggested for nighttime highway work. Five such categories were developed and range of

Table 5.6 Recommended Lighting Configuration for Various Construction Equipment

Type of Equipment	Min. Illumination Requirements lx (fc)	Lamp Power (watt)	Number of lamps		Beam Tilt (deg)	Height from ground		Equipment Height (m)
			Front	Rear		Front (m)	Rear (m)	
Slow-moving Equipment								
Paver	11 (1) at	Qtz 500	2	2	45	3.3	3.5	3.0
Milling Machine	4.9m (16ft)							4.7
Fast-moving Equipment								
Backhoe Loader	11 (1) at	Qtz 500	2	2	60	3.3	3.3	2.7
Wheel Tractor Scraper	17.7m (58ft)							3.7
Wheel Loader								4.8
Compactor/Roller								2.3
Motor Grader								3.1

illumination were suggested along with the space or task illumination and typical examples of highways tasks suitable for the categories.

A comparison with non-highway task matrix resulted in determination of average illuminance values for typical highway tasks. Based on these values corresponding categories were suggested. For construction equipment recommendations were provided by classifying all the equipment into two broad categories of fast and slow moving equipment. Glare control criteria was also evaluated and conclusions included in guidelines for equipment lighting.

CHAPTER 6
MODEL APPLICATION - CASE STUDIES

Introduction

Following the development of the model and illumination categories, it seemed important to validate the model and check its accuracy and feasibility. To demonstrate the applicability of the model, levels of illumination and categories developed in previous section, several case studies were chosen. For case studies selected construction sites on several FDOT projects were visited and data was recorded. The selection of these sites was based on their typical representation of commonly conducted nighttime highway construction operations and differences in the type of work. Recorded information using field observation forms is provided in Appendix A.

Data was recorded pertaining to position and value of illumination levels achieved on the job site, position and location of commonly deployed lighting equipment, and evaluation of light adequacy. Light meters and measuring tapes were used to measure levels and distances respectively. On site interviews were conducted to examine the quality and quantity of light. Various subjective tests to appraise the quality of light were also conducted. The projects chosen for the case studies include

1) Replacing Barrier wall, I-75, Gainesville, Florida.
2) Asphalt Paving of Intersection, Memorial Drive, Lakeland, Florida.

3) Bridge Deck, Fort Myers, Florida.

Various construction tasks in all the case studies were identified. The respective levels for the task were determined from the guidelines developed in chapter 5. The factor levels were also determined from the guidelines for all the tasks. These levels were assigned with predefined numerical values. The model formulated in Chapter 4 was employed to determine the levels from the regression equation. These computed levels were then compared with the assigned levels and checked against the actual recorded illumination levels. The subjective opinions of the construction crew, inspectors and other observers assisted in determining the adequacy and applicability of the computed levels as contrast to the actual lighting.

Case Study 1 : Replacing Barrier Wall

Description

Concrete barrier walls are usually placed between the travel and construction work zone as a traffic control measure and to separate traffic from working crew. Use of barrier wall is particularly crucial during long-term projects where lane closures are required for a substantial amount of time. Recently with increasing popularity of nighttime work they are also used as glare prevention measure for both the motorists and working crew. Before the work commences, barrier wall are placed to divert the traffic and to separate the closed lane from travel lane. Replacing barrier wall requires separating walls, lifting with the help of a loader and hauling on a flat-bed truck.

The project visited was on I-75 near Gainesville, Fl. Lighting was provided by Amida 4x1000 watt portable light plant. Equipment which were utilized included: 1) Wheel Loader

and 2) Flat-bed Truck. A field observation form as shown if Appendix A was used to collect information pertaining to lighting on site. A filled out observation form is provided in Appendix A, which provides all the details concerning the lighting provisions. Figure 6.1 shows the plan layout of the site and Figure 6.2 shows the perspective view of the work zone. The iso-candela lines and actual illumination levels are simulated using AGI software. The figures also show the actual values of illumination recorded on the job site.

Task Identification

On the project various tasks were identified. Table 6.1 provides all the details pertaining to the identified tasks and visual requirement.

Table 6.1 Task Identification for Barrier Wall Replacement Operation

Type of Task	Background Reflectance	Importance	Speed	Accuracy	Seeing Distance
Separating Walls	Medium	Low	Low	Low	1-5 ft
Fixing Hanger	Medium	Medium	Low	Low	1-5 ft
Lifting Walls	Low	Medium	Medium	Medium	>15 ft
Placing on Truck	Low	Medium	Medium	Medium	>15 ft

An attempt was made to identify visually most difficult and fatiguing tasks and it was determined that fixing hanger to wall was visually most difficult and placing on truck as visually most fatiguing task. Lifting walls and placing on trucks involved wheel loader and placing on truck also involved flat-bed truck.

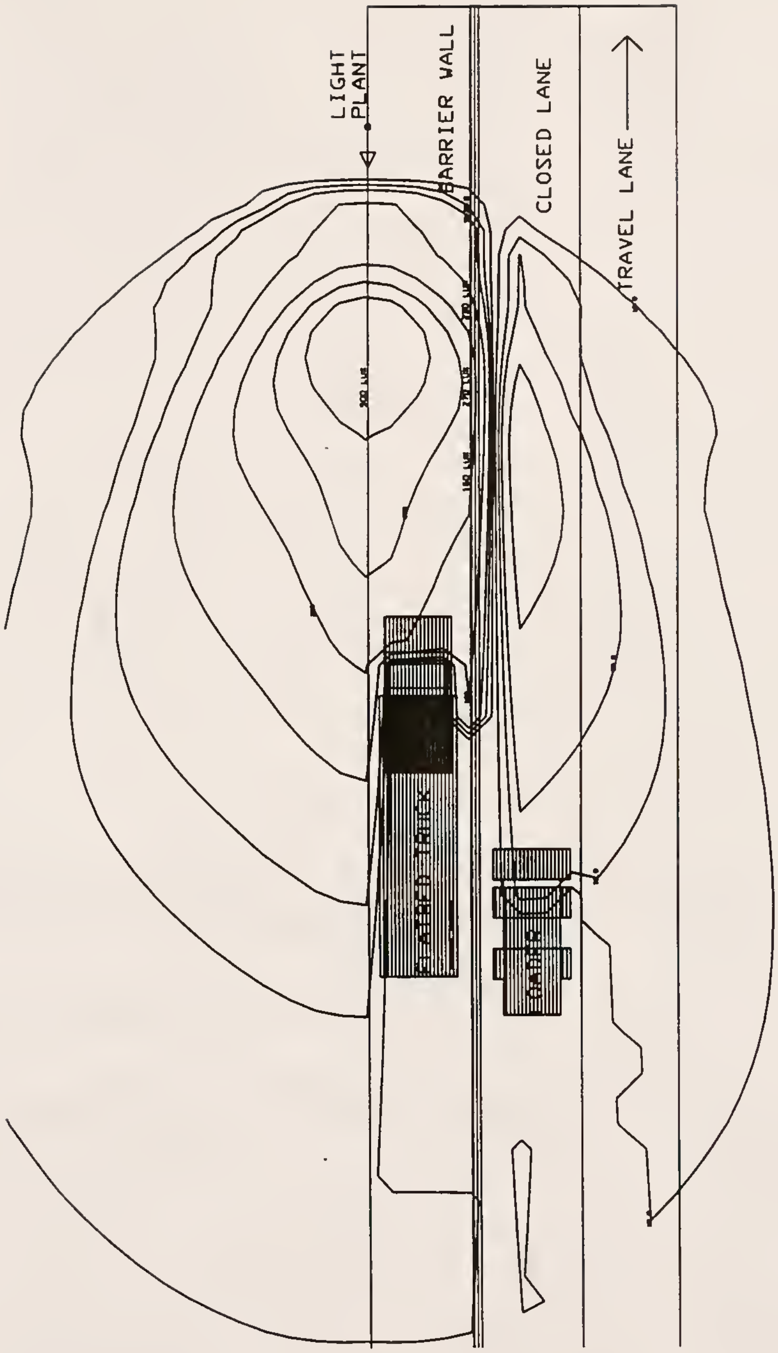


Figure 6.1 Plan Layout of Workzone (Case Study 1: Barrier Wall)

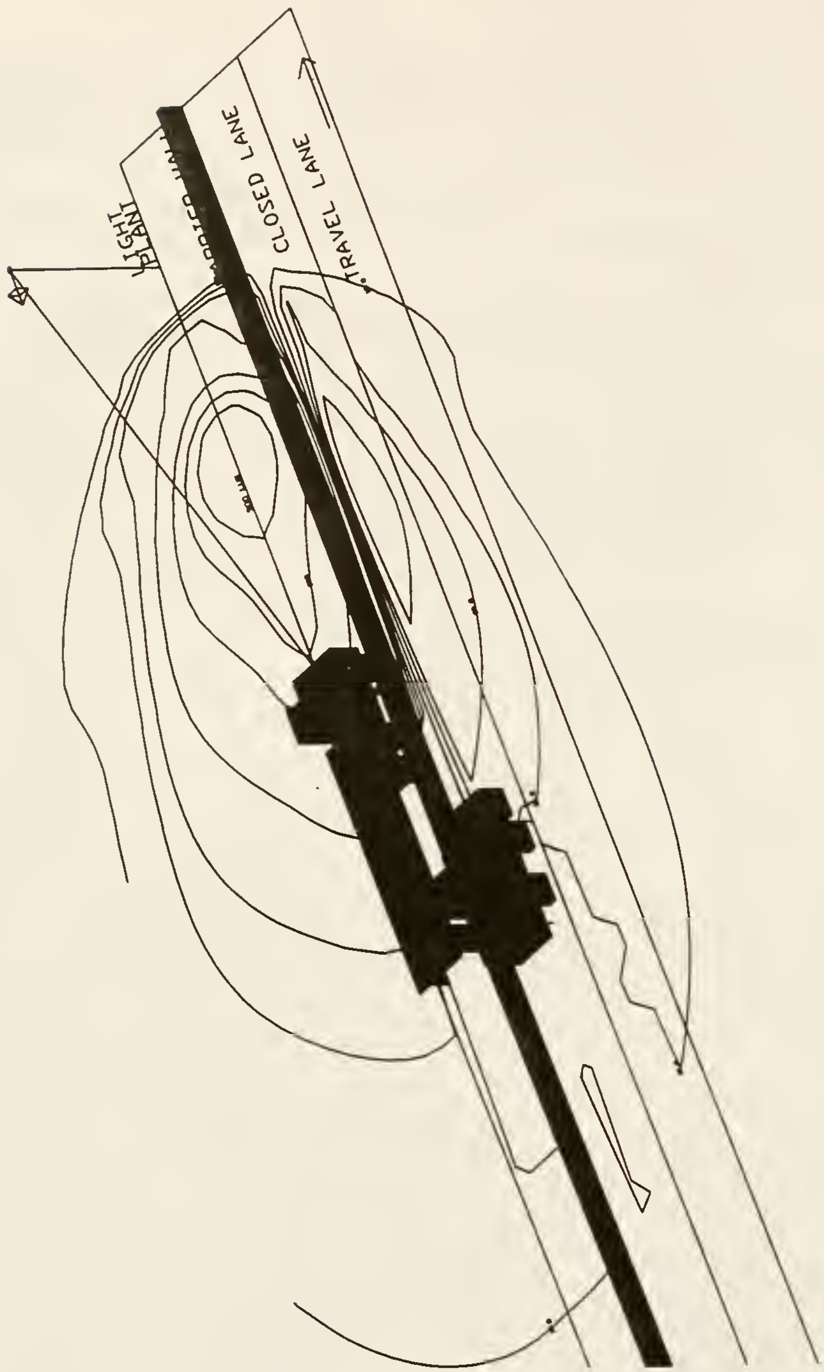


Figure 6.2 Perspective View of Workzone (Case Study 1: Barrier Wall)

Level Determination

To determine levels for the tasks, various factor levels were taken from the guidelines. For concrete barrier wall operation the subjective levels and numerical values of the factors are -

Importance of task	M	2
Background Reflection	M	2
Speed Associated	N	1
Relative Size	M	3
Seeing Distance	L	3

Using the regression equation and using the above numerical values for variables in the equation avearge illumination level is computed as 11.89 fc. From the guidelines the maintained illumination level for the barrier wall replacement is 10 fc and category II.

Comparison and Evaluation

From the measurements on site it was determined that the average illuminance levels for Task 1 were greater than 30 fc, for Task 2 greater than 20 fc, and for Task 3 and 4 they were more than 10 fc. Which conformed to the recommended lighting level from the guidelines and regression equation. It was also confirmed from on-site interviews and observations that the lighting was adequate to perform the operation.

Concerning quality of light, it was found that uniformity and diffusuin of light was satisfactory. Direction was not proper as the task associated with fixing the hanger did not

get sufficient lighting. Luminance was sufficient and lighting was adequate for most of the tasks to be performed comfortably. Glare to motorists and crew had some problems particularly because orientation of light plant was not proper. Veiling glare in absence of any highly reflective surface was found to be negligible. The walls were very bright and higher reflection coefficient. Equipment lighting increased the glare and did little to help illuminate the operation. Placement on truck was against the lighting plant and was under shadow.

Case Study 2 : Repaving Intersection

Description

The second case study involves asphalt repaving of an intersection. The project was situated on Memorial Drive at Lakeland, Florida in a semi-urban environment. The operation involved application of various equipment typically utilized for paving operations including: 1) Brush roller, 2) Asphalt spreader, 3) Paver and 4) Roller. For lighting Coleman light plant was used. The light plant was equipped with 4x1000 watt metal halide lamps mounted on a 25 ft high tower and titlted at an angle of 15 to 20 degrees. The plant was located 100 to 150 ft from the work place.

A filled out field observation form is included in Appendix A which provides other details concerning the job site and operation. Figure 6.3 shows the plan layout of the site and Figure 6.4 depicts the perspective view. The figures also show iso-candela lines at the work surface which were prepared by simulation using AGI.

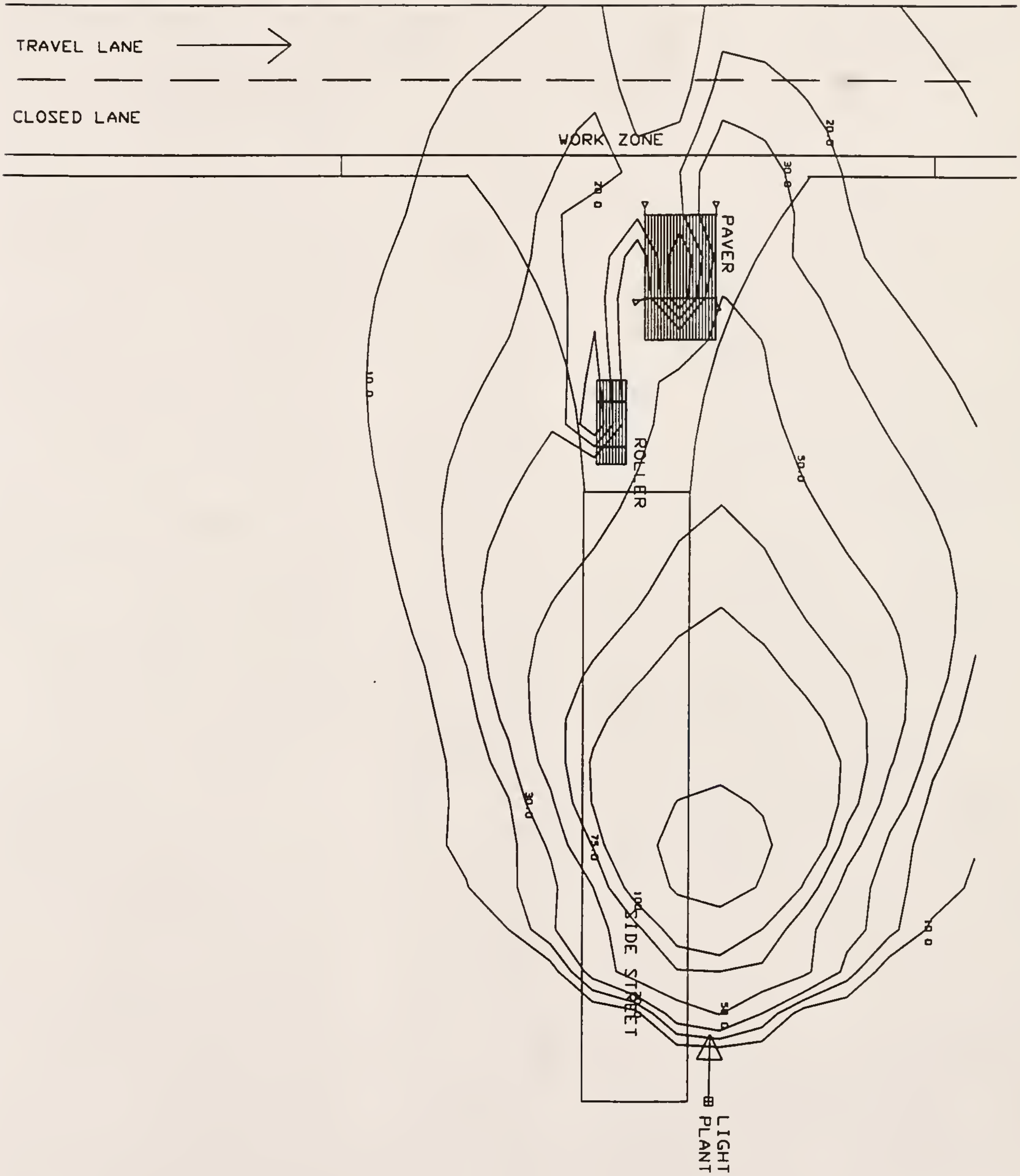


Figure 6.3 Plan Layout of Workzone (Case Study 2: Repaving Intersection)

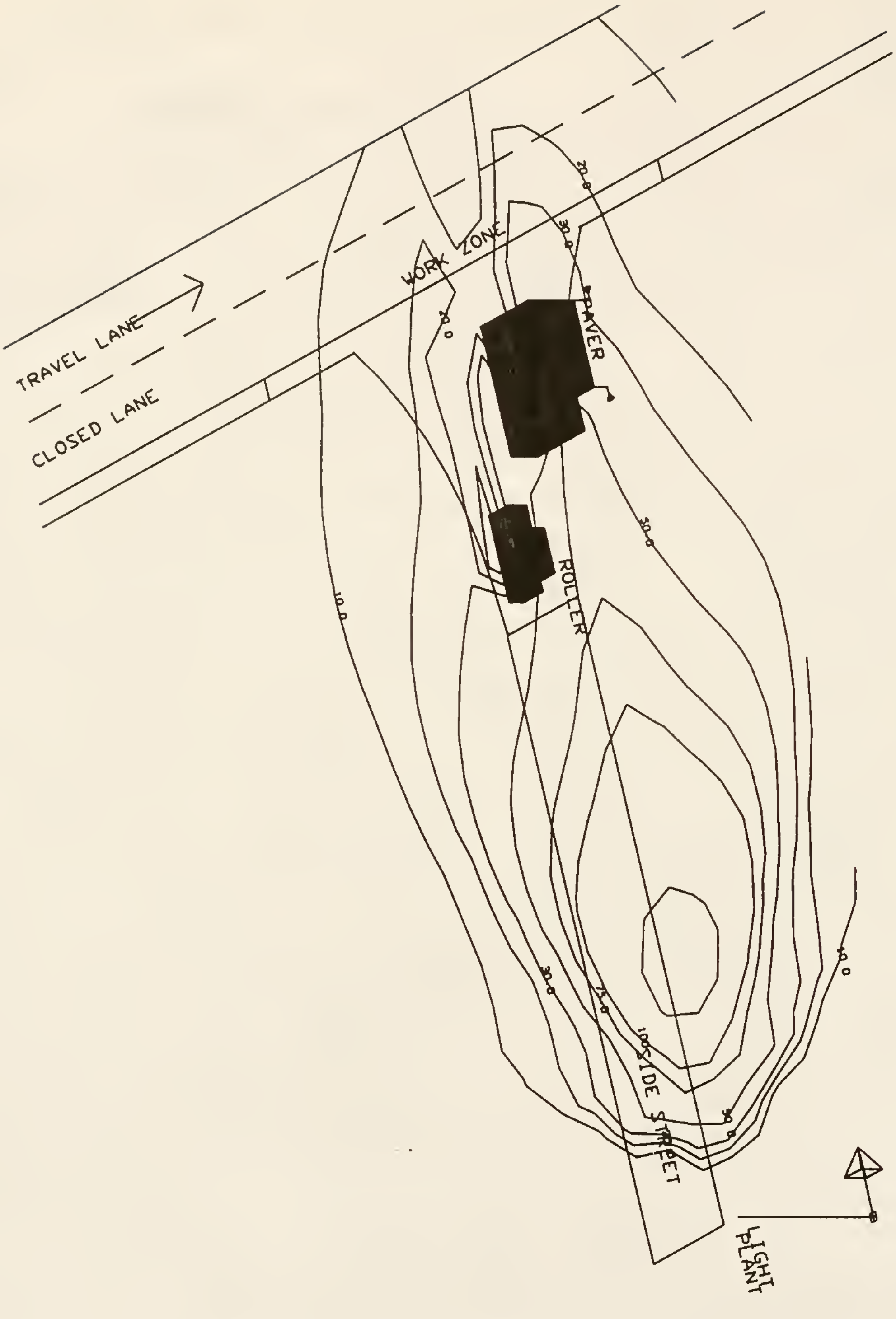


Figure 6.4 Perspective View of Workzone (Case Study 2: Repaving Intersection)

Task Identification

By observing the operation, several tasks were identified. Table 6.2 gives a listing of typical tasks involved in a paving operation and other characteristics associated with the tasks.

Table 6.2 Task Identification for Repaving Intersection Operation

Type of Tasks	Background Reflectance	Importance	Speed	Accuracy	Seeing Distance
Roller Brushing	Low	Low	Medium	Low	>15 ft
Spreading Asphalt	Low	Low	Low	Low	1-5 ft
Paving & Finishing	Low	High	Medium	High	5-15 ft
Compacting	Low	Medium	High	High	>15 ft

Visually dominating tasks were identified from the task list for which adequate lighting levels were determined. It was observed and found that task 3 i.e. paving and finishing was both visually most difficult and most fatiguing task. Therefore assigning a lighting level for this task would cover lighting requirements for the rest of the tasks too.

Level Determination

To determine lighting levels for the tasks, various factor levels were taken from the guidelines. For repaving operation the subjective levels and numerical values of the factors are

Importance of task	M	2
Background Reflection	H	3

Speed Associated	M	3
Relative Size	L	4
Seeing Distance	L	3

Using the regression equation and using the above numerical values for variables in the equation average illumination level for resurfacing is computed as 16.09 fc. From the guidelines the illumination level category for asphalt resurfacing is III and range 10-20 fc.

Comparison and Evaluation

The computed level was found to be more than the minimum desired and recommended by the guidelines. On-site measurements and observation revealed that the working levels for tasks were in the range of 1 fc for roller brushing, 3 fc for asphalt spreading, 5 to10 fc for paving and finishing, and 4 fc for roller compacting. Except for paving and finishing operation, actual lighting levels were found less than the recommnded levels. For finishing operation at some places lighting levels fall short of the suggested minimum and average levels.

Concerning quality of light, it was determined that uniformity and diffusion of light from the light plant was good. Direction of lighting was inappropriate and should have been from the side instead of end-lighting. Glare to drivers was found to be negligible, however roller operator was subjected to some glare. Their was no veiling glare and shielding from any glare. Lighting levels for roller brushing were inadequate. For asphalt spreading the orientation of lights was improper and spreading was done in a practically dark and shadow area. Which caused patches of area in between left out without asphalt. Similarly for

finishing work lighting was insufficient at some places and ground crew had difficulty in achieveing the desired quality. Lighting levels for paving, on the other hand, were adequate. For compacting task, the lighting achieved from the equipment lights was not satisfactory. The roller operator was essentially compacting on a pattern rather than visual information. Work being in the semi-urban environment had some ambient light. There was little traffic interference with the construction operation.

As a conclusion lighting was sufficient for the paver but compacting roller, brush roller, and asphalt spreader needed more equipment mounted lights. Lighting was not sufficient for inspection and finishing crew.

Case Study 3 : Bridge Deck Construction

Description

Project of bridge deck construction was visited in Fort Myers, Florida. The project was in a urban area but closed to traffic and with no or little ambient lighting. The project involved two separate operations: 1) Transfer of concrete and 2) Concrete pour. The first operation involved transfer of concrete from the trucks to the barges, hoisting by crane and transfer to conveyor. Concrete pour involved conveyor operation, concrete spreading, vibrating, and finishing. The equipment for first operation included concrete truck, crane and conveyor system and for second operation equipment were conveyor, vibrator, and screed. Lighting was provided by 3x1000 watt sodium vapor rectangular lamps on tower and 1000 watt metal halide lamps on crane for the first operation. For second operation various light plant were utilized including 500 watt quartz for conveyor lighting, 3x500 watt quartz and

2x1000 watt metal halide for screed lighting, and 1000 watt metal halide on finisher platform. The tower lights for concrete transfer from truck to buckets on barge were mounted on 20ft oriented 120 degrees from one another and having a tilt of 45 to 50 degrees. The hight difference between the bridge surface and barge was 30 ft.

Two filled out field observation forms, one for each operation is included in Appendix A. Figure 6.5 shows the plan layout of the second operation and Figure 6.6 gives the perspective view of the operation. The three horizontal bars in the figures represent conveyor, screed and finishing platform respectively. Iso-candelas lines are also drawn as a result of AGI simulation.

Tasks Identification

Tasks for the two operations were observed, identified and listed in Table 6.3. A total of eight tasks were identified, of which first four in the list belongs to the transfer of concrete operation and the rest four are associated with the concrete pour operation.

To identify the visually most challenging tasks, work process was analyzed closely. It was determined that transfer of concrete from bucket to conveyor and screed finishing were visually most difficult tasks. As visually most fatiguing tasks, two tasks were identified which inluded transfer of concrete from bucket to conveyor and spreading of concrete by shovel to the sides of the bridge deck.

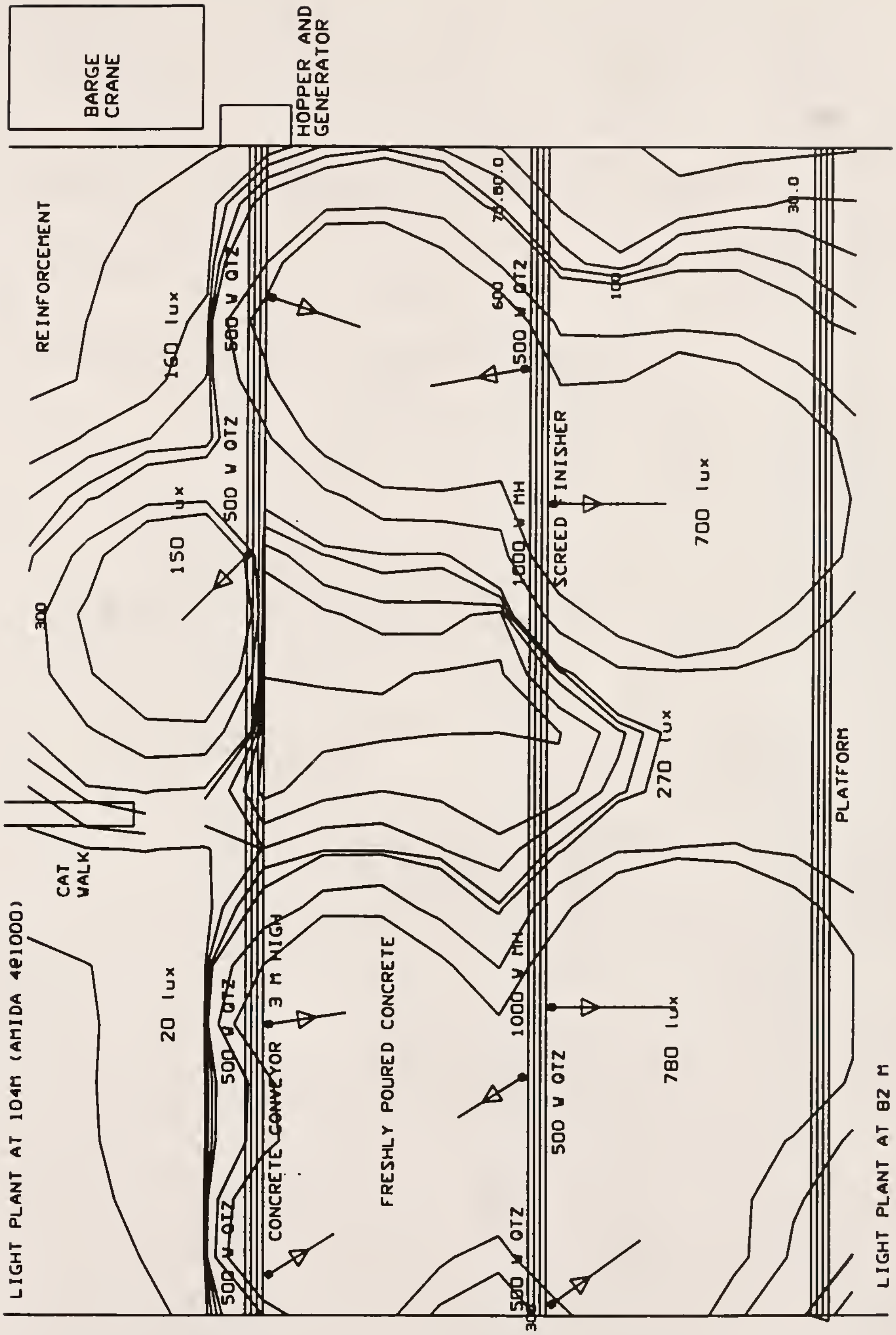


Figure 6.5 Plan Layout of Workzone (Case Study 3: Bridge Deck)

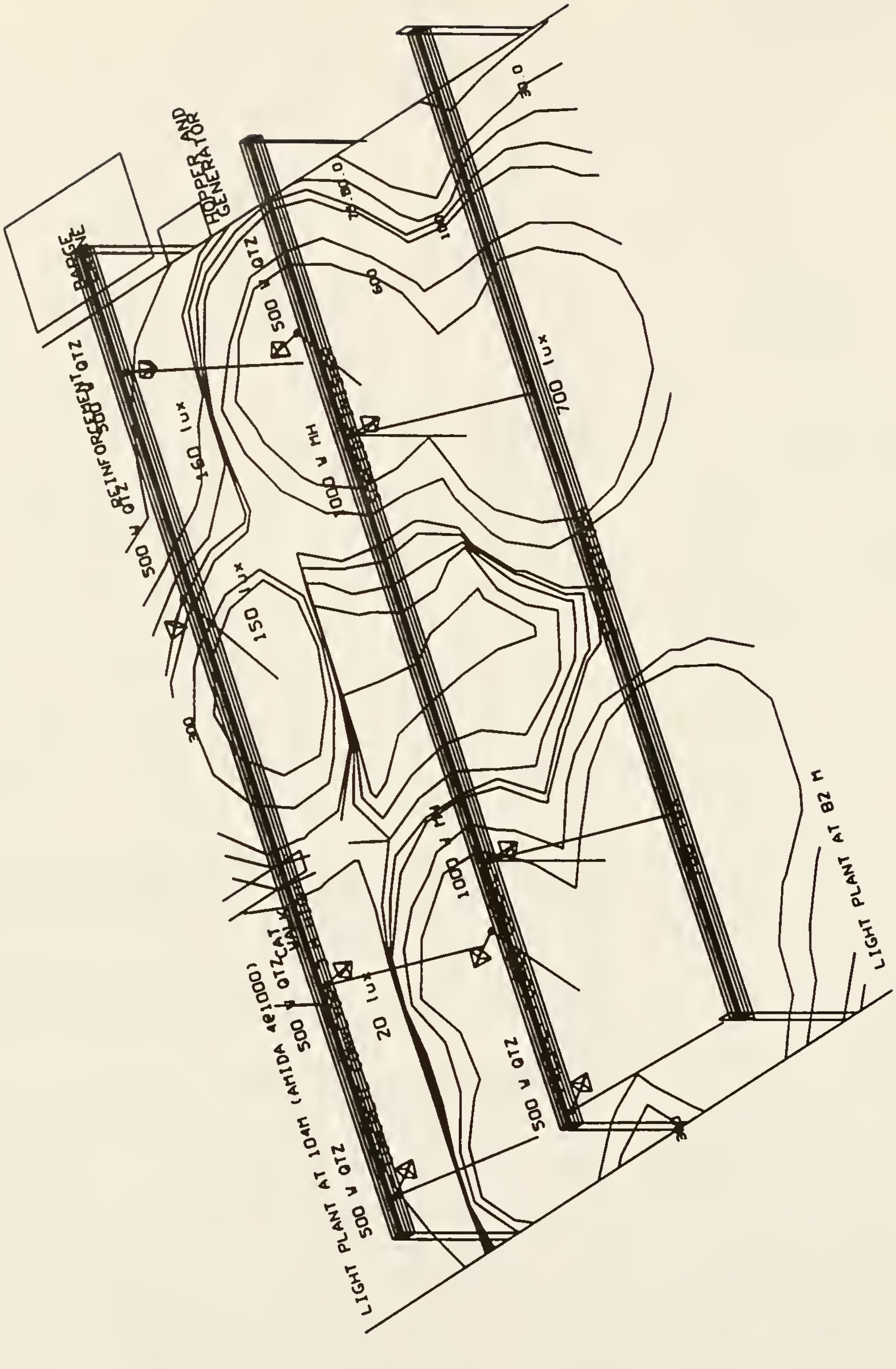


Figure 6.6 Perspective View of Workzone (Case Study 3: Bridge Deck)

Table 6.3 Task Identification for Bridge Deck Construction Operation

Type of Tasks	Background Reflectance	Importance	Speed	Accuracy	Seeing Distance
Concrete to chute	Medium	Low	Low	Low	5-15 ft
Buckets on barge	Medium	Low	Low	Medium	1-5 ft
Hoisting by crane	Low	Medium	Medium	Medium	>15 ft
Bucket to conveyor	Medium	Medium	Medium	Medium	1-5 ft
Conveyor Operation	Medium	Medium	Low	Low	>15 ft
Spreading by shovel	Low	Medium	Medium	Medium	1-5 ft
Vibrating concrete	Low	Medium	Medium	Medium	1-5 ft
Screed finishing	Low	High	High	High	5-15 ft

Level Determination

To determine levels for the tasks, various factor levels were taken from the guidelines. For bridge deck operation various identified tasks were analyzed and the subjective levels and numerical values of the factors for visually challenging tasks are

Importance of task	M	2
Background Reflection	L	1
Speed Associated	N	1
Relative Size	M	3
Seeing Distance	M	2

Using the regression equation and using the above numerical values for variables in the equation illumination level for bridge deck construction is computed as 22.13 fc. From

Comparison and Evaluation

The average illuminance level computed using the equation was found more than the minimum recommended by the guidelines. From measurements, actual lighting levels were determined to be - 2 to 15 fc for conveyor operation, 10 to 20 fc for concrete transfer from truck to bucket and to conveyor, 50 to 70 fc for screed and finishing platform.

Quantity of light was found satisfactory for most of the tasks except for spreading by shovel. This confirms and validates the model that the average lighting levels determined by the model are adequate to perform the operation. For spreading by shovel the illumination levels were less than the recommended values, which was confirmed by observing and interviewing the crew. Quality of light was found to be satisfactory regarding uniformity, diffusion and direction of light. Since no traffic was allowed, question of glare and interference did not arise. Glare was minimal to the crew and except from crane lighting and bridge lighting on barge, it was largely insignificant. There was some reflection from sides due to high reflectivity of concrete walls. There were two additional plants provided nearly 300 ft from the actual work site to illuminate the passage for crew and inspection.

Summary

In this chapter an attempt has been made to validate and examine the practical applicability of the regression model developed for various construction operations. The help of three case studies involving three different construction operations was taken to perform

of three case studies involving three different construction operations was taken to perform validation. The case studies included - a barrier wall replacing operation, asphalt resurfacing of an intersection, and concrete bridge deck construction. All the projects were located in Florida and enviroment for each was different.

Analysis included identification of tasks for each operation, determination of minimum recommended illumination levels from guidelines, factors and their levels, and computation of average level from the regression equation. This was followed by comparison and evaluation of actual levels recorded on site, quality and quantity of light, and adequacy of the provided lighting to perform the operation comfortably. Observation and subjective opinions of working crew and other experts were solicited to check the sufficiency of illumination. It was found that for certain tasks the illumination was satisfactory and for some it was not. In all cases lighting levels below than the recommended levels were found to be insufficient and levels above the suggested minimum levels were approved as adequate. This validated the model and confirmed that for any construction task, if subjective levels of various factors are known minimum average acceptable illumination levels can be determined.

CHAPTER 7
SUMMARY AND CONCLUSIONS

Summary

In this research effort an attempt has been made to identify the typical highway construction tasks performed at night and the factors affecting illumination requirement to adequately conduct these operations, and to develop a model determining average light intensity levels for the tasks. Various guidelines are also developed to recommend minimum illumination levels for certain tasks.

In an effort to provide an overview of nighttime highway construction and provisions for lighting, an extensive literature review was conducted. As a result of search no articles directly addressing the lighting in highway workzones were found. However, literature indicated that visual perception depends primarily on luminances in visual field, contrast, background reflectance, physical properties of objects, duration of exposure and, psychological and cognitive factors of the observer among many other factors. Lighting design, usually, follows a criteria, which include - illuminance criteria, luminance criteria and visibility criteria. The objective of these criteria is to determine adequacy and requirements of quality and quantity of a lighting design. Appraisal of human factors and their effects on lighting requirements indicated that human adaptation level and glare sensitivity are two of the important physical factors besides psychological considerations. The direct implications

of human factors and their influence on highway construction lighting requirements are reflected in safety, accidents, productivity and performance. Adequate lighting has been found to reduce accident rate and increase productivity. However, further increase in lighting levels above an optimum level did not affect productivity and performance significantly. During a review of existing standards and guidelines, IES and OSHA have been found to have extensive specifications and recommendations but were not associated with highway nighttime construction. Questionnaire surveys of various states and field reviews of FDOT projects showed lack of standardization as regards to illumination levels, equipment lighting and lighting plans. Most commonly encountered problems were glare to motorists, insufficient light on the task, and absence of consistent lighting practice.

A nationwide questionnaire survey of various state highway agencies indicated that nighttime highway construction work is becoming a common activity. Of the states responding to this study's survey, 85% reported performing nighttime work. Nearly 40% of the responding states use screen or barrier to avoid glare. Six states also reported having some sort of specification or provision to account for nighttime workzone lighting. These states include Connecticut, Florida, Maryland, Michigan, North Carolina, and Virginia. Most of such state guidelines are limited to one minimum illumination level, tower lighting and lighting for paver and roller.

In order to categorize typical highway nighttime work, various highway operations were identified. Preliminary list of most commonly performed tasks was sent to all the state highway agencies throughout the nation and to all district offices in Florida. Resurfacing, barrier walls, milling and removal were identified as some of most commonly performed construction operations.

Factors influencing illumination requirements for workzone lighting were also identified. These factors included: 1) human and cognitive factors, 2) environmental factors, 3) task-related factors including physical, operation, background, qualitative and equipment attributes, and 4) lighting factors. Of these factors, some of the significant factors were selected which included: a) speed, b) accuracy or importance, c) reflectance, d) seeing distance, and e) size of object. These factors were also assigned certain subjective levels for comparison and model development purposes.

A model approach was adopted to determine illumination levels for any construction task. Various regression models and their criteria for evaluation were discussed. Database of non-highway task matrix was developed for data analysis. For analysis purpose all the subjective factor levels were assigned with appropriate numerical values. Correlation analysis was performed to examine the association of various factors with illumination requirement. Trial models were suggested and analyzed using SAS procedures. Following the regression analysis, assumptions were checked and model adequacy was determined. Most appropriate regression model best-fitting the available data was selected.

In an attempt to develop illuminance level categories, five such categories were selected. The categories had illuminance ranges as less than five, five to10, 10 to 20, 20 to 30, and more than 30 foot-candles, respectively. Determination of these categories was based on IES and OSHA recommendations, various state provisions, opinions of experts and experiences during field reviews. The categories were intended to be interpreted as recommended safety requirements and not regulatory minimum requirements.

To compare with typical highway tasks, a list of non-highway tasks having similar

visual requirements was prepared and was assigned with appropriate factor levels. These factors levels were then compared with the highway task matrix and based on the comparison, illumination levels were recommended for highway tasks. Assigned levels and categories were prepared to develop guidelines for various highway tasks.

For equipment lighting standards, some SAE studies were utilized. It was determined that most of the highway construction equipment can be broadly categorized into two speed categories - slow moving and fast moving equipment. Distances to be illuminated at the front and back of these equipment were determined. For slow moving equipment this distance was found to be 16 ft (4.9 m) and for fast moving equipment, the value was 58 ft (17.7 m).

The regression model developed in the study needed to be validated and checked for practical application. For this three real life case studies were selected and model was applied. For all the three case studies which represented most commonly performed highway construction tasks at night, the results conformed to the actual and recommended values. From the opinions of the crew at the job-site and experiences while recording the observations, it was concluded that the results from the model were in agreement with the findings.

Conclusion

Nighttime highway construction work is now a common activity for many state highway agencies. Of the states responding to this study's survey, 85% reported performing nighttime work. Given the increased attention to avoiding traffic congestion, it appears likely that in the future more and more construction activity will be shifted to the nighttime.

Although lighting is the single most important and critical distinguishing factor

between day and night work, relatively few state highway agencies have addressed the issue of providing workzone lighting standards. Only six of the responding states indicated that they had any form of workzone lighting standard. Clearly, there is a need for detailed specifications and guidelines which include suggested illumination levels and glare control procedures.

In this study five illumination categories were selected. Because of the wide variance in the visibility requirements of different work tasks, a single standard was thought to be overly broad. The number of categories was limited to five in order to simplify implementation at the project level and yet address the variations in visual requirements for common construction tasks.

The next step in the development of the guidelines was to assign a suggested lighting category to each typical highway work and maintenance task. This development of recommended minimum illumination categories was based upon the following considerations:

1. Review of current lighting regulatory and industrial standards.
2. Review of current state highway agency workzone lighting standards.
3. Analysis and comparison of the established lighting standards for non-highway work activities with similar highway work activities.
4. Analysis of current industry practice obtained from project visits and contact with manufacturers.

Additionally, the question of how much lighted area to provide in advance of moving equipment was addressed. The required lighted area appears to be a function of the equipment operational characteristics and operator reaction time. It was concluded that 16ft and 58ft of illuminated area in the direction of travel for slow-moving and fast-moving equip-

ment respectively was sufficient. The width of lighted area around the equipment has been suggested as equal to the width of the lane.

A regression model to determine the average illumination requirement for any highway construction task was developed and tested with three real life case studies. It was concluded that the model is adequate to predict the lighting requirement for any highway nighttime construction task as long as its subjective factor levels are known. The validation also confirmed the practical feasibility of applying the model to any real life project.

Suggestions for Future Reasearch

Although the model is adequate in its applicability to any transportation facility construction during nighttime, it can be modified, improved and supplemented by additional models or systems. Certain issues which are considered important during the course of this study but are out of scope of work can be explored by further research. Some of such suggestions are as follows -

Glare Control

Glare to both the motorists and working crew is a serious concern in any highway workzone area. The model and study did not address the issue of glare control adequately. Although the concerns associated with both discomfort and disability types of glare were raised, it was neither included in the model nor in the guidelines. Further research can be conducted to examine the effects, quantification and control of glare and to incorporate in the model so that the prediction of illumination levels would also include considerations for glare.

Lighting Configuration

Although the study provided guidelines regarding light intensity levels recommended for the nighttime work, it does not address the issue of how to achieve these levels. Also the literature review included a discussion on type of light sources and their respective advantages and disadvantages but no recommendation was given on their application. Research may be required to simulate a typical workzone type situation and examine various lamps and their configuration to obtain the lighting levels suggested by this study. Glare control issues may also be combined with the determintaion of lighting configuration as the two are interdependent.

Additional Factors affecting Lighting Requirement

In the model described in this study only five factors were considered significant and the model is based on the subjective evaluation of these factors. The factors were limited by the availability of information concerning their effect and quantification. Additional research may be conducted to include various other factors in the model such as - uniformity, transient adaptation, glare criteria etc. However for this it is important to confirm that the factors have significant effect on lighting requirements for a task and that they can be either quantified or subjectively defined.

The model at present utilizes subjective determination of values for the five factors included in the model. Further research may be performed to objectify the factor levels and develop the model again according to the approach suggested in the study. This may include more reliability and consistency in the model in the prediction of illumination levels.

APPENDIX A

QUESTIONNAIRE SURVEY AND FIELD OBSERVATION FORMS

QUESTIONNAIRE SURVEY

for Maintenance

(Illumination During Nighttime Highway Work)

A. How many total maintenance projects are typically undertaken by the agency in a year ? [ ]

B. How many of these projects are nighttime projects (including the ones that are partly daytime & partly nighttime) ? [ ]

C. Following is a list of typical highway tasks. Please check appropriate boxes and add other tasks in the list which are performed by the agency at night and are not included in this list.

Task No.	Description of Tasks performed at night	Frequently	Occasionally	Rarely	Not at all
1.	Maintenance of earthwork/ embankment				
2.	Reworking Shoulders				
3.	Barrier Wall or Traffic Separator				
4.	Milling and Removal				
5.	Resurfacing				
6.	Repair of Concrete Pavement				
7.	Crack filling				
8.	Pot filling				
9.	Surface treatment				
10.	Waterproofing/ Sealing				
11.	Sidewalks repair & maintenance				
12.	Riprap maintenance				
13.	Resetting Guardrail/ fencing				
14.	Painting Stripes/ Pavement Markers				
15.	Landscaping/ Grassing/ Sodding				
16.	Highway Signing for maintenance works				
17.	Traffic Signals maintenance				
18.	Highway Lighting System - repair & maintenance				
19.	Bridge Decks rehabilitation & maintenance				
20.	Drainage Structures maintenance & rehabilitation				
21.	Sweeping and Cleanup				
22.	...				
23.	...				
24.	...				
25.	...				

D. Does the agency utilize screens or barriers between traveling lanes and workzone to avoid discomfort or disability glare to the motorists ?

Yes	No

If Yes, what kind of screens ? ______________________________

What criteria is used to determine when to use screens and to select a particular screen type ? Please discuss below or attach written criteria.

E. Does the agency have a set of Standards, Specifications or Guidelines to determine lighting requirements in the workzones for nighttime work ?

Yes	No

If Yes, would you please send us a copy of the same.
If No, how are lighting requirements determined ? Please explain.

F. Please list the name and address of the individual in the agency who is extensively involved with planning and design of workzone lighting requirements for the nighttime maintenance work.

Name : ______________________________

Position : ______________________________

Phone No : ______________________________

Address : ______________________________

____

____

____

Please complete this questionnaire and return to :

Dr. Ralph D. Ellis
Assistant Professor
Department of Civil Engineering
University of Florida
Gainesville, FL 32611

Phone : (904) 392-3730
Fax # : 904-392-3394

QUESTIONNAIRE SURVEY

for Construction

(Illumination During Nighttime Highway Work)

A. How many total construction projects are typically awarded by the agency in a year ?

B. How many of these projects are nighttime projects (including the ones that are partly daytime & partly nighttime) ?

C. Following is a list of typical highway tasks. Please check appropriate boxes and add other tasks in the list which are performed by the agency at night and are not included in this list.

Task No.	Descritlon of Tasks performed at night	Frequ-ently	Occasi-onally	Rarely	Not at all
1.	Excavation - regular, lateral ditch, channel				
2.	Embankment, Filling and Compaction				
3.	Barrier Walls, Traffic Separators				
4.	Milling and Removal				
5.	Resurfacing				
6.	Concrete Pavement construction				
7.	Subgrade stabilization & construction				
8.	Base Courses - clay, cement, asphalt				
9.	Surface treatment				
10.	Waterproofing/ Sealing				
11.	Sidewalks construction				
12.	Riprap placement				
13.	Guardrail, Fencing				
14.	Painting Stripes, Pavement Markers, Metal Buttons				
15.	Landscaping, Grassing, Sodding				
16.	Highway Signing for construction				
17.	Traffic Signals construction				
18.	Highway Lighting System construction				
19.	Bridge Decks construction				
20.	Drainage Structures, culverts & sewers construction				
21.	Construction of other Concrete Structures				
22.	...				
23.	...				
24.	...				
25.	...				

D. Does the agency utilize screens or barriers between traveling lanes and workzone to avoid discomfort or disability glare to the motorists ?

Yes	No

If Yes, what kind of screens ? ______________________________

What criteria is used to determine when to use screens and to select a particular screen type ? Please discuss below or attach written criteria.

E. Does the agency have a set of Standards, Specifications or Guidelines to determine lighting requirements in the workzones for nighttime work ?

Yes	No

If Yes, would you please send us a copy of the same.
If No, how are lighting requirements determined ? Please explain.

F. Please list the name and address of the individual in the agency who is extensively involved with planning and design of workzone lighting requirements for the nighttime construction work.

Name : ______________________________

Position : ______________________________

Phone No : ______________________________

Address : ______________________________

____

____

____

Please complete this questionnaire and return to :

Dr. Ralph D. Ellis
Assistant Professsor
Department of Civil Engineering
University of Florida
Gainesville, FL 32611

Phone : (904) 392-3730
Fax # : 904-392-3394

FIELD OBSERVATION FORM

(Illumination Guidelines for Nighttime Construction)

PROJECT INFORMATION

Type of Project : ______________________ **Type of operation :** ______________________

Location : ______________ **Date :** ______________ **Environment :** Urban Rural Semi-urban

TASK INFORMATION

Type of Tasks Task 1 ______________________ Task 3 ______________________

Task 2 ______________________ Task 4 ______________________

	Task 1	Task 2	Task 3	Task 4
Background Reflectance	High Med Low	High Med Low	High Med Low	High Med Low
Importance of the task	High Med Low	High Med Low	High Med Low	High Med Low
Speed of the task	High Med Low	High Med Low	High Med Low	High Med Low
Accuracy required for the task	High Med Low	High Med Low	High Med Low	High Med Low
Visually most difficult task	task 1	task 2	task 3	task 4
Visually most fatiguing task	task 1	task 2	task 3	task 4
Seeing distance (<1 ft, 1-5 ft, 5-15 ft, >15ft)	______ ft	______ ft	______ ft	______ ft

GENERAL LIGHTING INFORMATION

Equipments used

	Equipment 1	Lighting	Equipment 2	Lighting
Task 1		Good Ok Bad		Good Ok Bad
Task 2		Good Ok Bad		Good Ok Bad
Task 3		Good Ok Bad		Good Ok Bad
Task 4		Good Ok Bad		Good Ok Bad

Additional Lighting Fixed Portable Roadway Mounted Other ______________

Good Ok Insuff Need Change Power ______________

Configuration No. of Lamps ____________ Spacing ____________ Type of Lamps ______________

Height of Lamps ____________ Position ____________ Cover/shade ______________

No. of Lights ____________ Power ____________ Type of Lights ______________

Orientation ____________ Spread ____________ Angle from Vertical ______________

QUANTITY OF LIGHT

Illumination of surrounding	**Task 1**	High Suff Less Poor		**Task 3**	High Suff Less Poor	
	Task 2	High Suff Less Poor		**Task 4**	High Suff Less Poor	
Illumination of tasks	**Task 1**	High Suff Less Poor		**Task 3**	High Suff Less Poor	
	Task 2	High Suff Less Poor		**Task 4**	High Suff Less Poor	

QUALITY OF LIGHT

Uniformity of light	Good	Ok	Not ok	N/A		Comment	______
Direction	Good	Ok	Not ok	N/A		Comment	______
Diffusion of light	Good	Ok	Not ok	N/A		Comment	______
Luminence	Good	Ok	Not ok	N/A		Comment	______
Direct glare to Drivers	High	Medium	Low	None	N/A	Source	______
Direct glare to Crew	High	Medium	Low	None	N/A	Source	______
Shielding from Direct glare	Yes	No	N/A		Type of Sheild		______
Veiling glare to Driv.	High	Medium	Low	None	N/A	Source	______
Veiling glare to Crew	High	Medium	Low	None	N/A	Source	______
Shielding from Veiling glare	Yes	No	N/A		Type of Sheild		______

GENERAL INFORMATION

Age of Workers	< 40	40-55	55+	______		
Lighting designed by	DOT	Contractor	Consultant	Manufacturer	Other	______
Lighting provided by	DOT	Contractor	Consultant	Manufecturer	Other	______
Power for Lighting	Utility line	Generator	Others	______		

COMMENTS

About reflection from sides ______________________

About location of work ______________________

About traffic interference ______________________

Others ______________________

____

FIELD OBSERVATION FORM

(Illumination Guidelines for Nighttime Construction)

PROJECT INFORMATION

Type of Project : 26260-3446/3449 Type of operation : REPLACING BARRIER WALL

Location : I-75 GAINESVILLE Date : JUNE 9th 93 Environment : Urban Rural Semi-urban

TASK INFORMATION

Type of Tasks Task 1 SEPARATING WALLS Task 3 LIFTING WALLS

Task 2 FIXING HANGER TO WALL Task 4 PLACING ON TRUCK

	Task 1	Task 2	Task 3	Task 4
Background Reflectance	High Med Low	High Med Low	High Med Low	High Med Low
Importance of the task	High Med Low	High Med Low	High Med Low	High Med Low
Speed of the task	High Med Low	High Med Low	High Med Low	High Med Low
Accuracy required for the task	High Med Low	High Med Low	High Med Low	High Med Low
Visually most difficult task	task 1	task 2	task 3	task 4
Visually most fatiguing task	task 1	task 2	task 3	task 4
Seeing distance (I <1 ft, II 1-5 ft, III 5-15 ft, IV >15ft)	II ft	II ft	IV ft	IV ft

GENERAL LIGHTING INFORMATION

Equipments used

	Equipment 1	Lighting	Equipment 2	Lighting
Task 1	—	Good Ok Bad	—	Good Ok Bad
Task 2	—	Good Ok Bad	—	Good Ok Bad
Task 3	WHEEL LOADER	Good Ok Bad	—	Good Ok Bad
Task 4	WHEEL LOADER	Good Ok Bad	FLAT BED TRUCK	Good Ok Bad

Additional Lighting Fixed Portable Roadway Mounted Other PLANT

Good Ok Insuff Need Change Power 4 X 1000 W

Configuration No. of Lamps 1 Spacing — Type of Lamps AMIDA

Height of Lamps 30 FT Position 100-180 FT Cover/shade PARABOLIC

No. of Lights 4 Power 1000 Type of Lights METAL HALIDE

Orientation ALONG TRAVEL AGAINST TRAFFIC Spread NARROW BEAM Angle from Vertical 15°-20°

QUANTITY OF LIGHT

Illumination of surrounding	Task 1	High	Suff	Less	Poor	> 30	Task 3	High	Suff	Less	Poor	>10
	Task 2	High	Suff	Less	Poor	> 20	Task 4	High	Suff	Less	Poor	>10
Illumination of tasks	Task 1	High	Suff	Less	Poor	15 fc	Task 3	High	Suff	Less	Poor	5 fc
	Task 2	High	Suff	Less	Poor	5 fc	Task 4	High	Suff	Less	Poor	<5 fc

QUALITY OF LIGHT

Uniformity of light	Good	Ok	Not ok	N/A		Comment	Highly uniform throughout
Direction	Good	Ok	Not ok	N/A		Comment	Task 2 got less light
Diffusion of light	Good	Ok	Not ok	N/A		Comment	highly diffused light lamps
Luminence	Good	Ok	Not ok	N/A		Comment	very bright surroundings
Direct glare to Drivers	High	Medium	Low	None	N/A	Source	Plant was against traffic
Direct glare to Crew	High	Medium	Low	None	N/A	Source	Mostly for Task 3
Shielding from Direct glare	Yes	No	N/A		Type of Sheild		
Veiling glare to Driv.	High	Medium	Low	None	N/A	Source	
Veiling glare to Crew	High	Medium	Low	None	N/A	Source	Reflectivity wasn't high
Shielding from Veiling glare	Yes	No	N/A		Type of Sheild		

GENERAL INFORMATION

Age of Workers	< 40	40-55	55 +			
Lighting designed by	DOT	Contractor	Consultant	Manufacturer	Other	
Lighting provided by	DOT	Contractor	Consultant	Manufacturer	Other	
Power for Lighting	Utility line	Generetor	Others			

COMMENTS

About reflection from sides no reflections from sides, walls were bright

About location of work work very close to travel lane causing hazardous situation.

About traffic interference lifting of barricade walls ~~were~~ was causing interference with

Others travel lane. Glare from the plant for the motorists was severe. Equipment lighting increased the glare, however did not help the operation.

FIELD OBSERVATION FORM
(Illumination Guidelines for Nighttime Construction)

PROJECT INFORMATION

Type of Project : ______

Type of operation : ASPHALT PAVING INTER-SECTION

Location : MEMORIAL DRIVE LAKELAND, FL

Date : JUNE 1[th] 93

Environment : Urban Rural Semi-urban

TASK INFORMATION

Type of Tasks
Task 1 ROLLER BRUSHING
Task 2 SPREADING ASPHALT
Task 3 PAVING & FINISHING
Task 4 COMPACTING

	Task 1	Task 2	Task 3	Task 4
Background Reflectance	High Med Low	High Med Low	High Med Low	High Med Low
Importance of the task	High Med Low	High Med Low	High Med Low	High Med Low
Speed of the task	High Med Low	High Med Low	High Med Low	High Med Low
Accuracy required for the task	High Med Low	High Med Low	High Med Low	High Med Low
Visually most difficult task	task 1	task 2	task 3	task 4
Visually most fatiguing task	task 1	task 2	task 3	task 4
Seeing distance (I <1 ft, II 1-5 ft, III 5-15 ft, IV >15ft)	IV ft	II ft	III ft	IV ft

GENERAL LIGHTING INFORMATION

Equipments used

	Equipment 1	Lighting	Equipment 2	Lighting
Task 1	BRUSH ROLLER	Good Ok Bad		Good Ok Bad
Task 2	HAND SPREADER	Good Ok Bad		Good Ok Bad
Task 3	PAVER	Good Ok Bad		Good Ok Bad
Task 4	ROLLER	Good Ok Bad		Good Ok Bad

Additional Lighting: Fixed Portable Roadway Mounted Other LIGHT PLANT

Good Ok Insuff Need Change Power 4X1000 W

Configuration

No. of Lamps	1	Spacing	—	Type of Lamps	COLEMAN
Height of Lamps	25 FT	Position	100-150 FT	Cover/shade	PARABOLIC
No. of Lights	4	Power	1000 W	Type of Lights	METAL HALIDE
Orientation	TOWARDS INTERSECTION	Spread	NARROW BEAM	Angle from Vertical	15°-20°

QUANTITY OF LIGHT

Illumination of surrounding

Task 1	High Suff Less Poor	1 Fc	Task 3	High Suff Less Poor	3-4
Task 2	High Suff Less Poor	3 Fc	Task 4	High Suff Less Poor	3-4

Illumination of tasks

Task 1	High Suff Less Poor	1 Fc	Task 3	High Suff Less Poor	5-10
Task 2	High Suff Less Poor	3 Fc	Task 4	High Suff Less Poor	3-4

QUALITY OF LIGHT

Uniformity of light	Good	Ok	Not ok	N/A		Comment	throughout the paving area
Direction	Good	Ok	Not ok	N/A		Comment	Should have been from side
Diffusion of light	Good	Ok	Not ok	N/A		Comment	highly diffused light
Luminence	Good	Ok	Not ok	N/A		Comment	
Direct glare to Drivers	High	Medium	Low	None	N/A	Source	
Direct glare to Crew	High	Medium	Low	None	N/A	Source	
Shielding from Direct glare	Yes	No	N/A			Type of Sheild	
Veiling glare to Driv.	High	Medium	Low	None	N/A	Source	across the street
Veiling glare to Crew	High	Medium	Low	None	N/A	Source	some to roller operator
Shielding from Veiling glare	Yes	No	N/A			Type of Sheild	

GENERAL INFORMATION

Age of Workers	< 40	40-55	55+			
Lighting designed by	DOT	Contractor	Consultant	Manufacturer	Other	
Lighting provided by	DOT	Contractor	Consultant	Manufacturer	Other	
Power for Lighting	Utility line	Generator	Others			

COMMENTS

About reflection from sides not much reflection from sides

About location of work ambient lighting because of semi-urban environment

About traffic interference not much traffic interference because of lane closure.

Others severe glare to motorists as a result of another plant in operation along the travel lane, however for half of the operation this light plant did not serve much purpose

FIELD OBSERVATION FORM
(Illumination Guidelines for Nighttime Construction)

1/2

PROJECT INFORMATION

Type of Project : ______________

Type of operation : BRIDGE DECK CONSTN

Location : FORT MYERS, FL Date : June 15th, 93

Environment : Urban **Rural** Semi-urban

TASK INFORMATION — TRANSFER OF CONCRETE

Type of Tasks

Task 1 TRUCK TO CHUTE

Task 2 COLLECTION ON BARGE

Task 3 HOISTING BY CRANE

Task 4 BUCKET TO CONVEYOR

	Task 1	Task 2	Task 3	Task 4
Background Reflectance	High Med Low	High Med Low	High Med Low	High Med Low
Importance of the task	High Med Low	High Med Low	High Med Low	High Med Low
Speed of the task	High Med Low	High Med Low	High Med Low	High Med Low
Accuracy required for the task	High Med Low	High Med Low	High Med Low	High Med Low
Visually most difficult task	task 1	task 2	task 3	task 4
Visually most fatiguing task	task 1	task 2	task 3	task 4
Seeing distance (<1 ft, 1-5 ft, 5-15 ft, >15ft) I II III IV	III ft	II ft	IV ft	II ft

GENERAL LIGHTING INFORMATION

Equipments used

	Equipment 1	Lighting	Equipment 2	Lighting
Task 1	CONCRETE TRUCK	Good Ok Bad		Good Ok Bad
Task 2		Good Ok Bad		Good Ok Bad
Task 3	CRANE	Good Ok Bad		Good Ok Bad
Task 4	CONVEYOR SYSTEM	Good Ok Bad		Good Ok Bad

Additional Lighting: Fixed **Portable** Roadway Mounted Other LIGHT PLANT

Good **Ok** Insuff Need Change Power 3X1000

Configuration

No. of Lamps	1	Spacing	—	Type of Lamps	
Height of Lamps	20 FT - 1 50 FT - 2	Position	20 FT	Cover/shade	RECTANGULAR
No. of Lights	3	Power	1000	Type of Lights	SODIUM-VAPOR
Orientation	120° FROM EACH OTHER	Spread	OK	Angle from Vertical	45° 50°

TASK 1&2

TASK 3 – 3 LIGHTS ON CRANE, 30 FT, SPACED, ORIENTED TOWARDS THE HOIST (1000 W MH)

QUANTITY OF LIGHT

Illumination of surrounding	Task 1	High Suff Less Poor		Task 3	High Suff Less Poor
	Task 2	High Suff Less Poor		Task 4	High Suff Less Poor
Illumination of tasks	Task 1	High Suff Less Poor		Task 3	High Suff Less Poor
	Task 2	High Suff Less Poor		Task 4	High Suff Less Poor

QUALITY OF LIGHT

Uniformity of light	Good	Ok	Not ok	N/A		Comment	
Direction	Good	Ok	Not ok	N/A		Comment	
Diffusion of light	Good	Ok	Not ok	N/A		Comment	
Luminence	Good	Ok	Not ok	N/A		Comment	
Direct glare to Drivers	High	Medium	Low	None	N/A	Source	
Direct glare to Crew	High	Medium	Low	None	N/A	Source	FROM CRANE LIGHTS AND BRIDGE LIGHTS ON BARGE
Shielding from Direct glare	Yes	No	N/A		Type of Sheild		
Veiling glare to Driv.	High	Medium	Low	None	N/A	Source	
Veiling glare to Crew	High	Medium	Low	None	N/A	Source	
Shielding from Veiling glare	Yes	No	N/A		Type of Sheild		

GENERAL INFORMATION

Age of Workers	< 40	40-55	55 +			
Lighting designed by	DOT	Contractor	Consultant	Manufacturer	Other	
Lighting provided by	DOT	Contractor	Consultant	Manufacturer	Other	
Power for Lighting	Utility line	Generator	Others	BACK-UP GENERATOR		

COMMENTS

About reflection from sides: Some reflection from sides due to high reflectivity

About location of work: relatively more hazardous location but no traffic

About traffic interference: no interference as no traffic allowed

Others: for most part lighting was adequate to perform. There may be some glare to crew working on the barge and at conveyor system.

FIELD OBSERVATION FORM

(Illumination Guidelines for Nighttime Construction)

2/2

PROJECT INFORMATION

Type of Project : ______________ Type of operation : BRIDGE DECK CONSTN

Location : FORT MYERS , FL Date : June 15th, 93 Environment : Urban Rural Semi-urban

TASK INFORMATION – CONCRETE POUR

Type of Tasks Task 1 CONVEYOR OPERATION Task 3 VIBRATION G

Task 2 SPREADING BY SHOVEL Task 4 SCREED FINISHING

	Task 1	Task 2	Task 3	Task 4
Background Reflectance	High Med Low	High Med Low	High Med Low	High Med Low
Importance of the task	High Med Low	High Med Low	High Med Low	High Med Low
Speed of the task	High Med Low	High Med Low	High Med Low	High Med Low
Accuracy required for the task	High Med Low	High Med Low	High Med Low	High Med Low
Visually most difficult task	task 1	task 2	task 3	task 4
Visually most fatiguing task	task 1	task 2	task 3	task 4
Seeing distance (<1 ft, 1-5 ft, 5-15 ft, >15ft) I II III IV	IV ft	II ft	II ft	III ft

GENERAL LIGHTING INFORMATION

Equipments used

	Equipment 1	Lighting	Equipment 2	Lighting
Task 1	CONVEYOR	Good Ok Bad		Good Ok Bad
Task 2		Good Ok Bad		Good Ok Bad
Task 3	VIBRATOR	Good Ok Bad		Good Ok Bad
Task 4	SCREED	Good Ok Bad		Good Ok Bad

Additional Lighting Fixed Portable Roadway Mounted Other ______

Good Ok Insuff Need Change Power 4000 W

Configuration No. of Lamps 2 Spacing 150 – 200 FT Type of Lamps AMIDA

Height of Lamps 30 FT Position 100 FT Cover/shade PARABOLIC

No. of Lights 4 Power 1000 W Type of Lights METAL HALIDE

Orientation TOWARDS EACH OTHER ON BOTH SIDES Spread OK Angle from Vertical 25°

CONVEYOR LIGHTS: 500 W QTZ @ 10 FT HIGH , 4 NOS, ORIENTED DIFF.
SCREED LIGHTS: 3X500 W QTZ AND 2X1000W MH
FINISHER PLATFORM: 1X 1000 W MH @ 10 FT HIGH

QUANTITY OF LIGHT

Illumination of surrounding	Task 1	High Suff Less Poor		Task 3	High Suff Less Poor	
	Task 2	High Suff Less Poor		Task 4	High Suff Less Poor	
Illumination of tasks	Task 1	High Suff Less Poor		Task 3	High Suff Less Poor	
	Task 2	High Suff Less Poor		Task 4	High Suff Less Poor	

QUALITY OF LIGHT

Uniformity of light	Good	Ok	Not ok	N/A		Comment	
Direction	Good	Ok	Not ok	N/A		Comment	
Diffusion of light	Good	Ok	Not ok	N/A		Comment	
Luminance	Good	Ok	Not ok	N/A		Comment	
Direct glare to Drivers	High	Medium	Low	None	N/A	Source	
Direct glare to Crew	High	Medium	Low	None	N/A	Source	
Shielding from Direct glare	Yes	No	N/A		Type of Sheild		
Veiling glare to Driv.	High	Medium	Low	None	N/A	Source	
Veiling glare to Crew	High	Medium	Low	None	N/A	Source	
Shielding from Veiling glare	Yes	No	N/A		Type of Sheild		

GENERAL INFORMATION

Age of Workers	< 40	40-55	55 +			
Lighting designed by	DOT	Contractor	Consultant	Manufacturer	Other	
Lighting provided by	DOT	Contractor	Consultant	Manufacturer	Other	
Power for Lighting	Utility line	Generator	Others			

COMMENTS

About reflection from sides: Some reflections from sides because of concrete

About location of work: location less hazardous

About traffic interference: no traffic interference

Others: no major problems except Over heating of vibrators.

2 AMIDA 4X1000 MH light plants placed nearly 300 FT from work at both ends of the bridge.

APPENDIX B

SAS SOURCE CODE

```
LIBNAME LITE 'C:\SAS\SASWORK\';
DATA LITE.NONHIGH;
LENGTH ID $ 4 AREA $ 5 ACTIVITY $ 16;
INPUT ID $ AREA $ ACTIVITY $ F1 $ F2 $ F3 $ F4 $ F5 $ LEVEL;
CARDS;
IN1 Auto Frame_Assembly H M L S S 50
IN2 Auto Welding_Area  H H N S S 50
IN3 Auto Machining H H H F S 75
IN4 Auto Coal_Yards  L L N L L 0.5
IN5 Auto Substation   L L N L L 1.5
IN6 Auto Entrance  L L L M L 5
IN7 Auto Furnace_Area  H M N M S 30
IN8 Iron Mold_Yard  L L L M L 5
IN9 Iron Scrap_Yard M M N M L 10
IN10 Petro Pumps_valves L L N S M 5
IN11 Petro Heat_Exchangers L L N M L 3
IN12 Petro Maint_Platforms L L N L L 1
IN13 Petro Oper_Platforms L L L M L 5
IN14 Petro Cooling_Towers L L N S M 5
IN15 Petro Furnaces L L N M L 3
IN16 Petro Active_Stairs L L L M L 5
IN17 Petro General_Area L L N L L 1
IN18 Petro Extruder_Mixers  M M L M M 20
IN19 Petro Conveyors L M L M S 2
IN20 Petro Outdoor_Plants  L L N S M 5
IN21 Petro Substation L L N L M 2
IN22 Petro Road-freq_use L L M L L 0.4
IN23 Petro Road-infreq_use L L L L L 0.2
IN24 Petro Parking L L L L L 0.1
IN25 Petro Bulk_Storage  L L N L L 0.5
IN26 Petro Large_Bin L L N M M 5
IN27 Petro Small_Bin M M N S M 10
IN28 Petro Small_Parts M M N F M 20
IN29 Paper Mill_Grinder H M H S M 70
IN30 Paper Beater_Room H M L M M 30
IN31 Paper Roll_Dryer H H M M M 50
IN32 Paper Cutting_Sort H H H S S 70
IN33 Paper Warehouse M M L M M 20
IN34 Paper Shipping_Shed M M L M M 20
IN35 Paper Roadways L L M L L 0.4
IN36 Paper Log_Pile L L N M L 3
IN37 Paper Log_Unloading L L L M M 5
IN38 Ind Exacavation L L N L M 2
IN39 Ind General_Const  M M N M M 10
IN40 Ind Entrance-act L L L M L 5
IN41 Ind Entrance-inact L L N M L 1
IN42 Iron Hot_Top_Storage M H M M L 10;
PROC PRINT DATA=LITE.NONHIGH;
OPTIONS PAGESIZE=60 LINESIZE=65 NODATE NONUMBER;
```

```
TITLE 'Description of Factors and Illumination Levels';
TITLE2 'for Non-Highway Tasks';
RUN;

LIBNAME LITE 'C:\SAS\SASWORK\';
DATA LITE.NONHIGH1;
LENGTH ID $ 4 AREA $ 5 ACTIVITY $ 16;
INPUT ID $ AREA $ ACTIVITY $ F1 $ F2 $ F3 $ F4 $ F5 $ LEVEL;
IF F1='L' THEN F11=1;
IF F1='M' THEN F11=2;
IF F1='H' THEN F11=3;
IF F2='L' THEN F22=1;
IF F2='M' THEN F22=2;
IF F2='H' THEN F22=3;
IF F3='N' THEN F33=1;
IF F3='L' THEN F33=2;
IF F3='M' THEN F33=3;
IF F3='H' THEN F33=4;
IF F4='F' THEN F44=1;
IF F4='S' THEN F44=2;
IF F4='M' THEN F44=3;
IF F4='L' THEN F44=4;
IF F5='S' THEN F55=1;
IF F5='M' THEN F55=2;
IF F5='L' THEN F55=3;
CARDS;
IN1 Auto Frame_Assembly H M L S S 50
IN2 Auto Welding_Area  H H N S S 50
IN3 Auto Machining H H H F S 75
IN4 Auto Coal_Yards  L L N L L 0.5
IN5 Auto Substation   L L N L L 1.5
IN6 Auto Entrance  L L L M L 5
IN7 Auto Furnace_Area  H M N M S 30
IN8 Iron Mold_Yard  L L L M L 5
IN9 Iron Scrap_Yard M M N M L 10
IN10 Petro Pumps_valves L L N S M 5
IN11 Petro Heat_Exchangers L L N M L 3
IN12 Petro Maint_Platforms L L N L L 1
IN13 Petro Oper_Platforms L L L M L 5
IN14 Petro Cooling_Towers L L N S M 5
IN15 Petro Furnaces L L N M L 3
IN16 Petro Active_Stairs L L L M L 5
IN17 Petro General_Area L L N L L 1
IN18 Petro Extruder_Mixers  M M L M M 20
IN19 Petro Conveyors L M L M S 2
IN20 Petro Outdoor_Plants  L L N S M 5
IN21 Petro Substation L L N L M 2
IN22 Petro Road-freq_use L L M L L 0.4
IN23 Petro Road-infreq_use L L L L L 0.2
IN24 Petro Parking L L L L L 0.1
```

```
IN25 Petro Bulk_Storage  L L N L L 0.5
IN26 Petro Large_Bin L L N M M 5
IN27 Petro Small_Bin M M N S M 10
IN28 Petro Small_Parts M M N F M 20
IN29 Paper Mill_Grinder H M H S M 70
IN30 Paper Beater_Room H M L M M 30
IN31 Paper Roll_Dryer H H M M M 50
IN32 Paper Cutting_Sort H H H S S 70
IN33 Paper Warehouse M M L M M 20
IN34 Paper Shipping_Shed M M L M M 20
IN35 Paper Roadways L L M L L 0.4
IN36 Paper Log_Pile L L N M L 3
IN37 Paper Log_Unloading L L L M M 5
IN38 Ind Exacavation L L N L M 2
IN39 Ind General_Const  M M N M M 10
IN40 Ind Entrance-act L L L M L 5
IN41 Ind Entrance-inact L L N M L 1
IN42 Iron Hot_Top_Storage M H M M L 10
;
PROC PRINT;
OPTIONS PAGESIZE=60 NODATE NONUMBER;
TITLE 'Description of Factors and Illumination Levels';
TITLE2 'for Non-Highway Tasks';
RUN;

LIBNAME LITE 'C:\SAS\SASWORK\';
DATA LITE.HIGH1 LITE.HIGH2 LITE.HIGH3 LITE.HIGH4 LITE.HIGH5
LITE.HIGH6 LITE.HIGH7 LITE.HIGH8 LITE.HIGH9 LITE.HIGH10
LITE.HIGH11
LITE.HIGH12 LITE.HIGH13 LITE.HIGH14 LITE.HIGH15 LITE.HIGH16
LITE.HIGH17
LITE.HIGH18 LITE.HIGH19 LITE.HIGH20 LITE.HIGH21 LITE.HIGH22
LITE.HIGH23
LITE.HIGH24 LITE.HIGH25 LITE.HIGH26 LITE.HIGH27;
LENGTH HWID $ 4 TASK $ 17;
SET LITE.NONHIGH;
DO I=1 TO 27;
IF I=1 THEN DO;
HWID='HW01';TASK='Excavation';
FAC1='L'; FAC2='L'; FAC3='N'; FAC4='L'; FAC5='L';
END;
ELSE IF I=2 THEN DO;
HWID='HW02';TASK='Embankment';
FAC1='L'; FAC2='L'; FAC3='M'; FAC4='L'; FAC5='L';
END;
ELSE IF I=3 THEN DO;
HWID='HW03';TASK='Barrier Walls';
FAC1='M'; FAC2='M'; FAC3='N'; FAC4='M'; FAC5='L';
END;
ELSE IF I=4 THEN DO;
```

```
HWID='HW04';TASK='Milling';
FAC1='M'; FAC2='M'; FAC3='M'; FAC4='M'; FAC5='L';
END;
ELSE IF I=5 THEN DO;
HWID='HW05';TASK='Resurfacing';
FAC1='M'; FAC2='H'; FAC3='M'; FAC4='L'; FAC5='L';
END;
ELSE IF I=6 THEN DO;
HWID='HW06';TASK='Conc. Pavement';
FAC1='M'; FAC2='H'; FAC3='L'; FAC4='M'; FAC5='L';
END;
ELSE IF I=7 THEN DO;
HWID='HW07';TASK='Subgrade Stab.';
FAC1='L'; FAC2='L'; FAC3='L'; FAC4='L'; FAC5='M';
END;
ELSE IF I=8 THEN DO;
HWID='HW08';TASK='Base Courses';
FAC1='M'; FAC2='L'; FAC3='M'; FAC4='M'; FAC5='L';
END;
ELSE IF I=9 THEN DO;
HWID='HW09';TASK='Surface Treatment';
FAC1='M'; FAC2='H'; FAC3='M'; FAC4='L'; FAC5='L';
END;
ELSE IF I=10 THEN DO;
HWID='HW10';TASK='Waterproofing';
FAC1='M'; FAC2='H'; FAC3='M'; FAC4='M'; FAC5='M';
END;
ELSE IF I=11 THEN DO;
HWID='HW11';TASK='Sidewalks';
FAC1='M'; FAC2='M'; FAC3='L'; FAC4='L'; FAC5='M';
END;
ELSE IF I=12 THEN DO;
HWID='HW12';TASK='Riprap';
FAC1='M'; FAC2='M'; FAC3='L'; FAC4='M'; FAC5='M';
END;
ELSE IF I=13 THEN DO;
HWID='HW13';TASK='Guardrail';
FAC1='M'; FAC2='M'; FAC3='N'; FAC4='M'; FAC5='M';
END;
ELSE IF I=14 THEN DO;
HWID='HW14';TASK='Stripes/Markers';
FAC1='M'; FAC2='H'; FAC3='M'; FAC4='S'; FAC5='L';
END;
ELSE IF I=15 THEN DO;
HWID='HW15';TASK='Grass/Sodding';
FAC1='L'; FAC2='L'; FAC3='N'; FAC4='L'; FAC5='L';
END;
ELSE IF I=16 THEN DO;
HWID='HW16';TASK='Signing';
FAC1='M'; FAC2='M'; FAC3='N'; FAC4='M'; FAC5='M';
```

```
END;
ELSE IF I=17 THEN DO;
HWID='HW17';TASK='Signals';
FAC1='H'; FAC2='M'; FAC3='N'; FAC4='S'; FAC5='S';
END;
ELSE IF I=18 THEN DO;
HWID='HW18';TASK='Lighting System';
FAC1='H'; FAC2='M'; FAC3='N'; FAC4='S'; FAC5='M';
END;
ELSE IF I=19 THEN DO;
HWID='HW19';TASK='Bridge Decks';
FAC1='M'; FAC2='L'; FAC3='N'; FAC4='M'; FAC5='M';
END;
ELSE IF I=20 THEN DO;
HWID='HW20';TASK='Drainage Str.';
FAC1='M'; FAC2='M'; FAC3='N'; FAC4='L'; FAC5='M';
END;
ELSE IF I=21 THEN DO;
HWID='HW21';TASK='Concrete Str.';
FAC1='M'; FAC2='H'; FAC3='L'; FAC4='M'; FAC5='L';
END;
ELSE IF I=22 THEN DO;
HWID='HW22';TASK='Embank. Maint.';
FAC1='L'; FAC2='L'; FAC3='M'; FAC4='L'; FAC5='L';
END;
ELSE IF I=23 THEN DO;
HWID='HW23';TASK='Rewrk Shoulders';
FAC1='L'; FAC2='H'; FAC3='M'; FAC4='L'; FAC5='L';
END;
ELSE IF I=24 THEN DO;
HWID='HW24';TASK='Conc. Pvmt repair';
FAC1='M'; FAC2='M'; FAC3='M'; FAC4='S'; FAC5='M';
END;
ELSE IF I=25 THEN DO;
HWID='HW25';TASK='Crack Filling';
FAC1='H'; FAC2='M'; FAC3='L'; FAC4='F'; FAC5='M';
END;
ELSE IF I=26 THEN DO;
HWID='HW26';TASK='Pot Filling';
FAC1='M'; FAC2='M'; FAC3='N'; FAC4='F'; FAC5='M';
END;
ELSE IF I=27 THEN DO;
HWID='HW27';TASK='Reset Guardrail';
FAC1='M'; FAC2='M'; FAC3='N'; FAC4='M'; FAC5='M';
END;
SCORE=0;
IF F1=FAC1 THEN DO;
   SCORE=1;
   IF F2=FAC2 THEN SCORE=SCORE+1;
   IF F3=FAC3 THEN SCORE=SCORE+1;
```

```
   IF F4=FAC4 THEN SCORE=SCORE+1;
   IF F5=FAC5 THEN SCORE=SCORE+1;
   END;
DROP FAC1 FAC2 FAC3 FAC4 FAC5;
RENAME F1=IMPR F2=REFL F3=SPED F4=SIZE F5=DIST;
IF I=1 THEN OUTPUT LITE.HIGH1;
ELSE IF I=2 THEN OUTPUT LITE.HIGH2;
ELSE IF I=3 THEN OUTPUT LITE.HIGH3;
ELSE IF I=4 THEN OUTPUT LITE.HIGH4;
ELSE IF I=5 THEN OUTPUT LITE.HIGH5;
ELSE IF I=6 THEN OUTPUT LITE.HIGH6;
ELSE IF I=7 THEN OUTPUT LITE.HIGH7;
ELSE IF I=8 THEN OUTPUT LITE.HIGH8;
ELSE IF I=9 THEN OUTPUT LITE.HIGH9;
ELSE IF I=10 THEN OUTPUT LITE.HIGH10;
ELSE IF I=11 THEN OUTPUT LITE.HIGH11;
ELSE IF I=12 THEN OUTPUT LITE.HIGH12;
ELSE IF I=13 THEN OUTPUT LITE.HIGH13;
ELSE IF I=14 THEN OUTPUT LITE.HIGH14;
ELSE IF I=15 THEN OUTPUT LITE.HIGH15;
ELSE IF I=16 THEN OUTPUT LITE.HIGH16;
ELSE IF I=17 THEN OUTPUT LITE.HIGH17;
ELSE IF I=18 THEN OUTPUT LITE.HIGH18;
ELSE IF I=19 THEN OUTPUT LITE.HIGH19;
ELSE IF I=20 THEN OUTPUT LITE.HIGH20;
ELSE IF I=21 THEN OUTPUT LITE.HIGH21;
ELSE IF I=22 THEN OUTPUT LITE.HIGH22;
ELSE IF I=23 THEN OUTPUT LITE.HIGH23;
ELSE IF I=24 THEN OUTPUT LITE.HIGH24;
ELSE IF I=25 THEN OUTPUT LITE.HIGH25;
ELSE IF I=26 THEN OUTPUT LITE.HIGH26;
ELSE IF I=27 THEN OUTPUT LITE.HIGH27;
END;
DATA LITE.HIGHWAY;
SET LITE.HIGH1 LITE.HIGH2 LITE.HIGH3 LITE.HIGH4 LITE.HIGH5
LITE.HIGH6 LITE.HIGH7 LITE.HIGH8 LITE.HIGH9 LITE.HIGH10
LITE.HIGH11
LITE.HIGH12 LITE.HIGH13 LITE.HIGH14 LITE.HIGH15 LITE.HIGH16
LITE.HIGH17
LITE.HIGH18 LITE.HIGH19 LITE.HIGH20 LITE.HIGH21 LITE.HIGH22
LITE.HIGH23
LITE.HIGH24 LITE.HIGH25 LITE.HIGH26 LITE.HIGH27;
IF SCORE<4 THEN DELETE;
DROP I;
PROC SORT DATA=LITE.HIGHWAY;
  BY HWID DESCENDING SCORE;
RUN;
PROC PRINT DATA=LITE.HIGHWAY;
  BY HWID TASK;
  ID ID;
```

```
OPTIONS PAGESIZE=60 LINESIZE=65 NODATE NONUMBER;
TITLE 'Comparison of Highway Tasks with';
TITLE2 'equivalent Non-Highway Tasks';
RUN;
PROC MEANS MEAN;
  VAR LEVEL;
  BY HWID TASK;
  TITLE 'Mean Illuminance Levels as determined';
  TITLE2'by comparing Highway & Non-highway Tasks';
RUN;
PROC PLOT;
  PLOT LEVEL*HWID / HAXIS=HW01 HW02 HW03 HW04 HW05 HW06 HW07
HW08 HW09 HW10 HW11 HW12 HW13 HW14;
TITLE  'Illumination Levels vs Highway Tasks';
TITLE2 '(levels obtained from equivalent non-highway
tasks)';
RUN;
PROC PLOT;
  PLOT LEVEL*HWID / HAXIS=HW15 HW16 HW17 HW18 HW19 HW20 HW21
HW22 HW23 HW24 HW25 HW26 HW27;
RUN;
proc plot data=lite.nonhigh1;
  options pagesize=50 linesize=65 nodate nonumber;
  plot level*f11='*' level*f22='@' level*f33='o'
level*f44='#'
       level*f55='+' /overlay;
run;
proc corr data=lite.nonhigh1;
  var level f11 f22 f33 f44 f55;
  title 'Correlation between Illumination and Various
Factors';
run;
proc reg data=lite.nonhigh1;
  title 'Illumination vs Importance';
  model level=f11/ r;
  var f22 f33 f44 f55;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Reflectivity';
  model level=f22/ r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Speed';
  model level=f33/ r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Size';
  model level=f44/ r;
  plot residual.*level / symbol='*';
run;
```

```
  title 'Illumination vs Distance';
  model level=f55/ r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Importance, Reflection & Size';
  model level=f11 f22 f44/ r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Importance, Reflection & Speed';
  model level=f11 f22 f33/ r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Importance, Reflection & Distance';
  model level=f11 f22 f55/ r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Importance, Speed & Size';
  model level=f11 f33 f44/r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Imp, Refl, Speed & Size';
  model level=f11 f22 f33 f44/ r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Imp, Refl, Size & Distance';
  model level=f11 f22 f44 f55/ r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs Imp, Speed, Size & Distance';
  model level=f11 f33 f44 f55/ r;
  plot residual.*level / symbol='*';
run;
  title 'Illumination vs All Five Factors';
  model level=f11 f22 f33 f44 f55/ r;
  plot residual.*level / symbol='*';
run;
proc reg data=lite.nonhigh1;
  title 'Model';
  model level=f11 f22 f33 f44 f55/ selection=maxr cp;
run;
```

APPENDIX C

SAS OUTPUT

Description of Factors and Illumination Levels
for Non-Highway Tasks

OBS	ID	AREA	ACTIVITY	F1	F2	F3	F4	F5	LEVEL	F11	F22	F33	F44	F55
1	IN1	Auto	Frame_Assembly	H	M	L	S	S	50.0	3	2	2	2	1
2	IN2	Auto	Welding_Area	H	H	N	S	S	50.0	3	3	1	2	1
3	IN3	Auto	Machining	H	H	H	F	S	75.0	3	3	4	1	1
4	IN4	Auto	Coal_Yards	L	L	N	L	L	0.5	1	1	1	4	3
5	IN5	Auto	Substation	L	L	N	L	L	1.5	1	1	1	4	3
6	IN6	Auto	Entrance	L	L	L	M	L	5.0	1	1	2	3	3
7	IN7	Auto	Furnace_Area	H	M	N	M	S	30.0	3	2	1	3	1
8	IN8	Iron	Mold_Yard	L	L	L	M	L	5.0	1	1	2	3	3
9	IN9	Iron	Scrap_Yard	M	M	N	M	L	10.0	2	2	1	3	3
10	IN10	Petro	Pumps_valves	L	L	N	S	M	5.0	1	1	1	2	2
11	IN11	Petro	Heat_Exchangers	L	L	N	M	L	3.0	1	1	1	3	3
12	IN12	Petro	Maint_Platforms	L	L	N	L	L	1.0	1	1	1	4	3
13	IN13	Petro	Oper_Platforms	L	L	L	M	L	5.0	1	1	2	3	3
14	IN14	Petro	Cooling_Towers	L	L	N	S	M	5.0	1	1	1	2	2
15	IN15	Petro	Furnaces	L	L	N	M	L	3.0	1	1	1	3	3
16	IN16	Petro	Active_Stairs	L	L	L	M	L	5.0	1	1	2	3	3
17	IN17	Petro	General_Area	L	L	N	L	L	1.0	1	1	1	4	3
18	IN18	Petro	Extruder_Mixers	M	M	L	M	M	20.0	2	2	2	3	2
19	IN19	Petro	Conveyors	L	M	L	M	S	2.0	1	2	2	3	1
20	IN20	Petro	Outdoor_Plants	L	L	N	S	M	5.0	1	1	1	2	2
21	IN21	Petro	Substation	L	L	N	L	M	2.0	1	1	1	4	2
22	IN22	Petro	Road-freq_use	L	L	M	L	L	0.4	1	1	3	4	3
23	IN23	Petro	Road-infreq_use	L	L	L	L	L	0.2	1	1	2	4	3
24	IN24	Petro	Parking	L	L	L	L	L	0.1	1	1	2	4	3
25	IN25	Petro	Bulk_Storage	L	L	N	L	L	0.5	1	1	1	4	3
26	IN26	Petro	Large_Bin	L	L	N	M	M	5.0	1	1	1	3	2
27	IN27	Petro	Small_Bin	M	M	N	S	M	10.0	2	2	1	2	2
28	IN28	Petro	Small_Parts	M	M	N	F	M	20.0	2	2	1	1	2
29	IN29	Paper	Mill_Grinder	H	M	H	S	M	70.0	3	2	4	2	2
30	IN30	Paper	Beater_Room	H	M	L	M	M	30.0	3	2	2	3	2
31	IN31	Paper	Roll_Dryer	H	H	M	M	M	50.0	3	3	3	3	2
32	IN32	Paper	Cutting_Sort	H	H	H	S	S	70.0	3	3	4	2	1
33	IN33	Paper	Warehouse	M	M	L	M	M	20.0	2	2	2	3	2
34	IN34	Paper	Shipping_Shed	M	M	L	M	M	20.0	2	2	2	3	2
35	IN35	Paper	Roadways	L	L	M	L	L	0.4	1	1	3	4	3
36	IN36	Paper	Log_Pile	L	L	N	M	L	3.0	1	1	1	3	3
37	IN37	Paper	Log_Unloading	L	L	L	M	M	5.0	1	1	2	3	2
38	IN38	Ind	Exacavation	L	L	N	L	M	2.0	1	1	1	4	2
39	IN39	Ind	General_Const	M	M	N	M	M	10.0	2	2	1	3	2
40	IN40	Ind	Entrance-act	L	L	L	M	L	5.0	1	1	2	3	3
41	IN41	Ind	Entrance-inact	L	L	N	M	L	1.0	1	1	1	3	3
42	IN42	Iron	Hot_Top_Storage	M	H	M	M	L	10.0	2	3	3	3	3

Correlation between Level of Ill. and Factors

CORRELATION ANALYSIS

6 'VAR' Variables: LEVEL F11 F22 F33 F44 F55

Simple Statistics

Variable	N	Mean	Std Dev	Sum
LEVEL	42	14.68095	20.93419	616.60000
F11	42	1.57143	0.80070	66.00000
F22	42	1.52381	0.70670	64.00000
F33	42	1.73810	0.91223	73.00000
F44	42	2.97619	0.81114	125.00000
F55	42	2.33333	0.72134	98.00000

Simple Statistics

Variable	Minimum	Maximum
LEVEL	0.10000	75.00000
F11	1.00000	3.00000
F22	1.00000	3.00000
F33	1.00000	4.00000
F44	1.00000	4.00000
F55	1.00000	3.00000

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0/N=42

	LEVEL	F11	F22	F33	F44	F55
LEVEL	1.00000	0.89875	0.78973	0.61789	-0.61867	-0.68150
	0.0	0.0001	0.0001	0.0001	0.0001	0.0001
F11	0.89875	1.00000	0.88055	0.44364	-0.54184	-0.67566
	0.0001	0.0	0.0001	0.0033	0.0002	0.0001
F22	0.78973	0.88055	1.00000	0.48283	-0.53084	-0.63795
	0.0001	0.0001	0.0	0.0012	0.0003	0.0001
F33	0.61789	0.44364	0.48283	1.00000	-0.20640	-0.19768
	0.0001	0.0033	0.0012	0.0	0.1897	0.2095
F44	-0.61867	-0.54184	-0.53084	-0.20640	1.00000	0.59749
	0.0001	0.0002	0.0003	0.1897	0.0	0.0001
F55	-0.68150	-0.67566	-0.63795	-0.19768	0.59749	1.00000
	0.0001	0.0001	0.0001	0.2095	0.0001	0.0

APPENDIX D

SUMMARY OF FACTOR COMPARISON FOR LEVELS

Comparison of Highway Tasks with
equivalent Non-Highway Tasks

------------------ HWID=HW01 TASK=Excavation ------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN4	Auto	Coal_Yards	L	L	N	L	L	0.5	5
IN5	Auto	Substation	L	L	N	L	L	1.5	5
IN12	Petro	Maint_Platforms	L	L	N	L	L	1.0	5
IN17	Petro	General_Area	L	L	N	L	L	1.0	5
IN25	Petro	Bulk_Storage	L	L	N	L	L	0.5	5
IN11	Petro	Heat_Exchangers	L	L	N	M	L	3.0	4
IN15	Petro	Furnaces	L	L	N	M	L	3.0	4
IN21	Petro	Substation	L	L	N	L	M	2.0	4
IN22	Petro	Road-freq_use	L	L	M	L	L	0.4	4
IN23	Petro	Road-infreq_use	L	L	L	L	L	0.2	4
IN24	Petro	Parking	L	L	L	L	L	0.1	4
IN35	Paper	Roadways	L	L	M	L	L	0.4	4
IN36	Paper	Log_Pile	L	L	N	M	L	3.0	4
IN38	Ind	Exacavation	L	L	N	L	M	2.0	4
IN41	Ind	Entrance-inact	L	L	N	M	L	1.0	4

------------------ HWID=HW02 TASK=Embankment ------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN22	Petro	Road-freq_use	L	L	M	L	L	0.4	5
IN35	Paper	Roadways	L	L	M	L	L	0.4	5
IN4	Auto	Coal_Yards	L	L	N	L	L	0.5	4
IN5	Auto	Substation	L	L	N	L	L	1.5	4
IN12	Petro	Maint_Platforms	L	L	N	L	L	1.0	4
IN17	Petro	General_Area	L	L	N	L	L	1.0	4
IN23	Petro	Road-infreq_use	L	L	L	L	L	0.2	4
IN24	Petro	Parking	L	L	L	L	L	0.1	4
IN25	Petro	Bulk_Storage	L	L	N	L	L	0.5	4

---------------- HWID=HW03 TASK=Barrier Walls ----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN9	Iron	Scrap_Yard	M	M	N	M	L	10	5
IN39	Ind	General_Const	M	M	N	M	M	10	4

------------------- HWID=HW04 TASK=Milling -------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN9	Iron	Scrap_Yard	M	M	N	M	L	10	4
IN42	Iron	Hot_Top_Storage	M	H	M	M	L	10	4

----------------- HWID=HW05 TASK=Resurfacing -----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN42	Iron	Hot_Top_Storage	M	H	M	M	L	10	4

---------------- HWID=HW06 TASK=Conc. Pavement ----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE

IN42	Iron	Hot_Top_Storage	M	H	M	M	L	10	4

----------------- HWID=HW07 TASK=Subgrade Stab. -----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN21	Petro	Substation	L	L	N	L	M	2.0	4
IN23	Petro	Road-infreq_use	L	L	L	L	L	0.2	4
IN24	Petro	Parking	L	L	L	L	L	0.1	4
IN37	Paper	Log_Unloading	L	L	L	M	M	5.0	4
IN38	Ind	Exacavation	L	L	N	L	M	2.0	4

------------------ HWID=HW08 TASK=Base Courses ------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN42	Iron	Hot_Top_Storage	M	H	M	M	L	10	4

--------------- HWID=HW09 TASK=Surface Treatment ---------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN42	Iron	Hot_Top_Storage	M	H	M	M	L	10	4

----------------- HWID=HW10 TASK=Waterproofing ------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN42	Iron	Hot_Top_Storage	M	H	M	M	L	10	4

------------------- HWID=HW11 TASK=Sidewalks --------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN18	Petro	Extruder_Mixers	M	M	L	M	M	20	4
IN33	Paper	Warehouse	M	M	L	M	M	20	4
IN34	Paper	Shipping_Shed	M	M	L	M	M	20	4

--------------------- HWID=HW12 TASK=Riprap --------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN18	Petro	Extruder_Mixers	M	M	L	M	M	20	5
IN33	Paper	Warehouse	M	M	L	M	M	20	5
IN34	Paper	Shipping_Shed	M	M	L	M	M	20	5
IN39	Ind	General_Const	M	M	N	M	M	10	4

------------------- HWID=HW13 TASK=Guardrail --------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN39	Ind	General_Const	M	M	N	M	M	10	5
IN9	Iron	Scrap_Yard	M	M	N	M	L	10	4
IN18	Petro	Extruder_Mixers	M	M	L	M	M	20	4
IN27	Petro	Small_Bin	M	M	N	S	M	10	4
IN28	Petro	Small_Parts	M	M	N	F	M	20	4
IN33	Paper	Warehouse	M	M	L	M	M	20	4
IN34	Paper	Shipping_Shed	M	M	L	M	M	20	4

---------------- HWID=HW14 TASK=Stripes/Markers ----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN42	Iron	Hot_Top_Storage	M	H	M	M	L	10	4

----------------- HWID=HW15 TASK=Grass/Sodding -----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN4	Auto	Coal_Yards	L	L	N	L	L	0.5	5
IN5	Auto	Substation	L	L	N	L	L	1.5	5
IN12	Petro	Maint_Platforms	L	L	N	L	L	1.0	5
IN17	Petro	General_Area	L	L	N	L	L	1.0	5
IN25	Petro	Bulk_Storage	L	L	N	L	L	0.5	5
IN11	Petro	Heat_Exchangers	L	L	N	M	L	3.0	4
IN15	Petro	Furnaces	L	L	N	M	L	3.0	4
IN21	Petro	Substation	L	L	N	L	M	2.0	4
IN22	Petro	Road-freq_use	L	L	M	L	L	0.4	4
IN23	Petro	Road-infreq_use	L	L	L	L	L	0.2	4
IN24	Petro	Parking	L	L	L	L	L	0.1	4
IN35	Paper	Roadways	L	L	M	L	L	0.4	4
IN36	Paper	Log_Pile	L	L	N	M	L	3.0	4
IN38	Ind	Exacavation	L	L	N	L	M	2.0	4
IN41	Ind	Entrance-inact	L	L	N	M	L	1.0	4

-------------------- HWID=HW16 TASK=Signing --------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN39	Ind	General_Const	M	M	N	M	M	10	5
IN9	Iron	Scrap_Yard	M	M	N	M	L	10	4
IN18	Petro	Extruder_Mixers	M	M	L	M	M	20	4
IN27	Petro	Small_Bin	M	M	N	S	M	10	4
IN28	Petro	Small_Parts	M	M	N	F	M	20	4
IN33	Paper	Warehouse	M	M	L	M	M	20	4
IN34	Paper	Shipping_Shed	M	M	L	M	M	20	4

-------------------- HWID=HW17 TASK=Signals --------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN1	Auto	Frame_Assembly	H	M	L	S	S	50	4
IN2	Auto	Welding_Area	H	H	N	S	S	50	4
IN7	Auto	Furnace_Area	H	M	N	M	S	30	4

---------------- HWID=HW18 TASK=Lighting System ----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN29	Paper	Mill_Grinder	H	M	H	S	M	70	4

----------------- HWID=HW19 TASK=Bridge Decks -----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN39	Ind	General_Const	M	M	N	M	M	10	4

---------------- HWID=HW20 TASK=Drainage Str. -----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN27	Petro	Small_Bin	M	M	N	S	M	10	4
IN28	Petro	Small_Parts	M	M	N	F	M	20	4
IN39	Ind	General_Const	M	M	N	M	M	10	4

----------------- HWID=HW21 TASK=Concrete Str. -----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN42	Iron	Hot_Top_Storage	M	H	M	M	L	10	4

----------------- HWID=HW22 TASK=Embank. Maint. -----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN22	Petro	Road-freq_use	L	L	M	L	L	0.4	5
IN35	Paper	Roadways	L	L	M	L	L	0.4	5
IN4	Auto	Coal_Yards	L	L	N	L	L	0.5	4
IN5	Auto	Substation	L	L	N	L	L	1.5	4
IN12	Petro	Maint_Platforms	L	L	N	L	L	1.0	4
IN17	Petro	General_Area	L	L	N	L	L	1.0	4
IN23	Petro	Road-infreq_use	L	L	L	L	L	0.2	4
IN24	Petro	Parking	L	L	L	L	L	0.1	4
IN25	Petro	Bulk_Storage	L	L	N	L	L	0.5	4

---------------- HWID=HW23 TASK=Rewrk Shoulders ----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN22	Petro	Road-freq_use	L	L	M	L	L	0.4	4
IN35	Paper	Roadways	L	L	M	L	L	0.4	4

--------------- HWID=HW24 TASK=Conc. Pvmt repair ---------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN27	Petro	Small_Bin	M	M	N	S	M	10	4

----------------- HWID=HW25 TASK=Crack Filling -----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN30	Paper	Beater_Room	H	M	L	M	M	30	4

------------------ HWID=HW26 TASK=Pot Filling ------------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN28	Petro	Small_Parts	M	M	N	F	M	20	5
IN27	Petro	Small_Bin	M	M	N	S	M	10	4
IN39	Ind	General_Const	M	M	N	M	M	10	4

---------------- HWID=HW27 TASK=Reset Guardrail ----------------

ID	AREA	ACTIVITY	IMPR	REFL	SPED	SIZE	DIST	LEVEL	SCORE
IN39	Ind	General_Const	M	M	N	M	M	10	5
IN9	Iron	Scrap_Yard	M	M	N	M	L	10	4
IN18	Petro	Extruder_Mixers	M	M	L	M	M	20	4

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IN27 Petro Small_Bin          M    M    N    S    M    10    4
IN28 Petro Small_Parts        M    M    N    F    M    20    4
IN33 Paper Warehouse          M    M    L    M    M    20    4
IN34 Paper Shipping_Shed      M    M    L    M    M    20    4

                Mean Illuminance Levels as determined
              by comparing Highway & Non-highway Tasks

                      Analysis Variable : LEVEL


-------------------- HWID=HW01 TASK=Excavation ------------------
                                 Mean
                             ------------
                                1.3066667
                             ------------

-------------------- HWID=HW02 TASK=Embankment ------------------
                                 Mean
                             ------------
                                0.6222222
                             ------------

------------------ HWID=HW03 TASK=Barrier Walls -----------------
                                 Mean
                             ------------
                               10.0000000
                             ------------

--------------------- HWID=HW04 TASK=Milling --------------------
                                 Mean
                             ------------
                               10.0000000
                             ------------

------------------- HWID=HW05 TASK=Resurfacing ------------------
                                 Mean
                             ------------
                               10.0000000
                             ------------

------------------ HWID=HW06 TASK=Conc. Pavement ----------------
                                 Mean
                             ------------
                               10.0000000
                             ------------

------------------ HWID=HW07 TASK=Subgrade Stab. ----------------
                                 Mean
                             ------------
                                1.8600000
                             ------------

------------------- HWID=HW08 TASK=Base Courses -----------------
                                 Mean
                             ------------
                               10.0000000
                             ------------

---------------- HWID=HW09 TASK=Surface Treatment ---------------
```

```
                        Mean
                   ------------
                     10.0000000
                   ------------

------------------ HWID=HW10 TASK=Waterproofing -----------------
                        Mean
                   ------------
                     10.0000000
                   ------------

-------------------- HWID=HW11 TASK=Sidewalks -------------------
                        Mean
                   ------------
                     20.0000000
                   ------------

---------------------- HWID=HW12 TASK=Riprap --------------------
                        Mean
                   ------------
                     17.5000000
                   ------------

-------------------- HWID=HW13 TASK=Guardrail -------------------
                        Mean
                   ------------
                     15.7142857
                   ------------

----------------- HWID=HW14 TASK=Stripes/Markers ----------------
                        Mean
                   ------------
                     10.0000000
                   ------------

------------------ HWID=HW15 TASK=Grass/Sodding -----------------
                        Mean
                   ------------
                      1.3066667
                   ------------

--------------------- HWID=HW16 TASK=Signing --------------------
                        Mean
                   ------------
                     15.7142857
                   ------------

--------------------- HWID=HW17 TASK=Signals --------------------
                        Mean
                   ------------
                     43.3333333
                   ------------

----------------- HWID=HW18 TASK=Lighting System ----------------
                        Mean
                   ------------
                     70.0000000
                   ------------

------------------- HWID=HW19 TASK=Bridge Decks -----------------
```

```
                           Mean
                       ------------
                        10.0000000
                       ------------

------------------ HWID=HW20 TASK=Drainage Str. -----------------
                           Mean
                       ------------
                        13.3333333
                       ------------

------------------ HWID=HW21 TASK=Concrete Str. -----------------
                           Mean
                       ------------
                        10.0000000
                       ------------

------------------ HWID=HW22 TASK=Embank. Maint. ----------------
                           Mean
                       ------------
                         0.6222222
                       ------------

----------------- HWID=HW23 TASK=Rewrk Shoulders ----------------
                           Mean
                       ------------
                         0.4000000
                       ------------

---------------- HWID=HW24 TASK=Conc. Pvmt repair ---------------
                           Mean
                       ------------
                        10.0000000
                       ------------

------------------ HWID=HW25 TASK=Crack Filling -----------------
                           Mean
                       ------------
                        30.0000000
                       ------------

------------------- HWID=HW26 TASK=Pot Filling ------------------
                           Mean
                       ------------
                        13.3333333
                       ------------

----------------- HWID=HW27 TASK=Reset Guardrail ----------------
                           Mean
                       ------------
                        15.7142857
                       ------------
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